MONTHLY WEATHER REVIEW

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As the national meteorological service for the United States, the Weather Bureau issues several periodicals, serials, and miscellaneous publications on weather, climate, and meteorological science as required to carry out its public service functions. The principal periodicals and serials are described on this page and on the inside of the back cover. A more complete listing of Weather Bureau publications is available upon request to Chief, U. S. Weather Bureau, Washington 25, D. C.

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MONTHLY WEATHER REVIEW

First published in 1872, the Monthly Weather Review serves as a medium of publication for technical contributions in the field of meteorology, principally in the branches of synoptic and applied meteorology. In addition each issue contains an article descriptive of the atmospheric circulation during the month over the Northern Hemisphere with particular reference to the effect on weather in the United States. A second article deals with some noteworthy feature of the month's weather. Illustrated. Annual subscription: Domestic, $3.50; Foreign, $4.50; 30¢ per copy. Subscription to the *Review* does not include the *Supplements* which have been issued irregularly and are for sale separately.

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(Continued on inside back cover)

The Weather Bureau desires that the *Monthly Weather Review* serve as a medium of publication for original contributions within its field, but the publication of a contribution is not to be construed as official approval of the views expressed.

The issue for each month is published as promptly as monthly data can be assembled for preparation of the review of the weather of the month. In order to maintain the schedule with the Public Printer, no proofs will be sent to authors outside of Washington, D. C.

The printing of this publication has been approved by the Director of the Bureau of the Budget, February 11, 1952.

DEPARTMENT OF COMMERCE
SINCLAIR WEEKS, Secretary

WEATHER BUREAU
F. W. REICHELDERFER, Chief

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RECORDED PRESSURE DISTRIBUTION IN THE OUTER PORTION OF A TORNADO VORTEX

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[Manuscript received December 29, 1953]

ABSTRACT

Records are presented from nine barographs located in a small area close to the path of a tornado. The pressure profile in the range from 720 to 2,300 feet from the path of the tornado center as determined from the barograph records was found to be in good agreement with calculations based on a simple model consisting of a frictionless vortex with in-flow.

INTRODUCTION

On June 8, 1953, a tornado passed through a portion of the Lewis Flight Propulsion Laboratory of the National Advisory Comittee for Aeronautics located at the Cleveland-Hopkins Airport, Cleveland, Ohio. A total of eight barographs were in operation at various locations within the laboratory at the time. These instruments plus one additional barograph at the United States Weather Bureau Station nearby provided records of the pressure changes during the passage of the tornado at distances from the path of the center varying from 720 to 2,300 feet.

The principal purpose of this paper is to present the pressure data and other pertinent information, since it is believed that the observations may be of considerable value in the study of the dynamics of tornadoes. A simple analysis, in which the observed pressure distribution is compared with the theoretical distribution calculated for a vortex with in-flow, is also included.

Appreciation is extended to the United States Weather Bureau for providing a copy of the barogram and other meteorological data from the Weather Bureau Airport Station, Cleveland, Ohio.

GENERAL DESCRIPTION OF STORM

The tornado approached from the west and passed through the southern part of the Lewis Laboratory at about 9:45 p. m. EDT, continuing on an east-northeasterly heading across the Airport. The tornado was associated with a severe thunderstorm with almost continuous cloud-to-cloud lightning. Hailstones up to about an inch in diameter fell in many areas on both sides of the tornado path and one reliable report of hail the size of hen's eggs was received. Hail was not observed at the Airport.

An aerial survey was made the following day to determine the general path of the tornado from areas west of Cleveland to its disappearance over Lake Erie on the east side of Cleveland. It was possible to plot this path from observations of points of destruction such as damaged dwellings and farm buildings and uprooted trees. The plot of the path of the tornado is shown on the map in figure 1. It will be noted from this plot that the tornado maintained almost a straight easterly heading for about 37 miles west of Cleveland Airport and then about at the Airport turned northeasterly to a heading of approximately 55 degrees through the densely populated areas

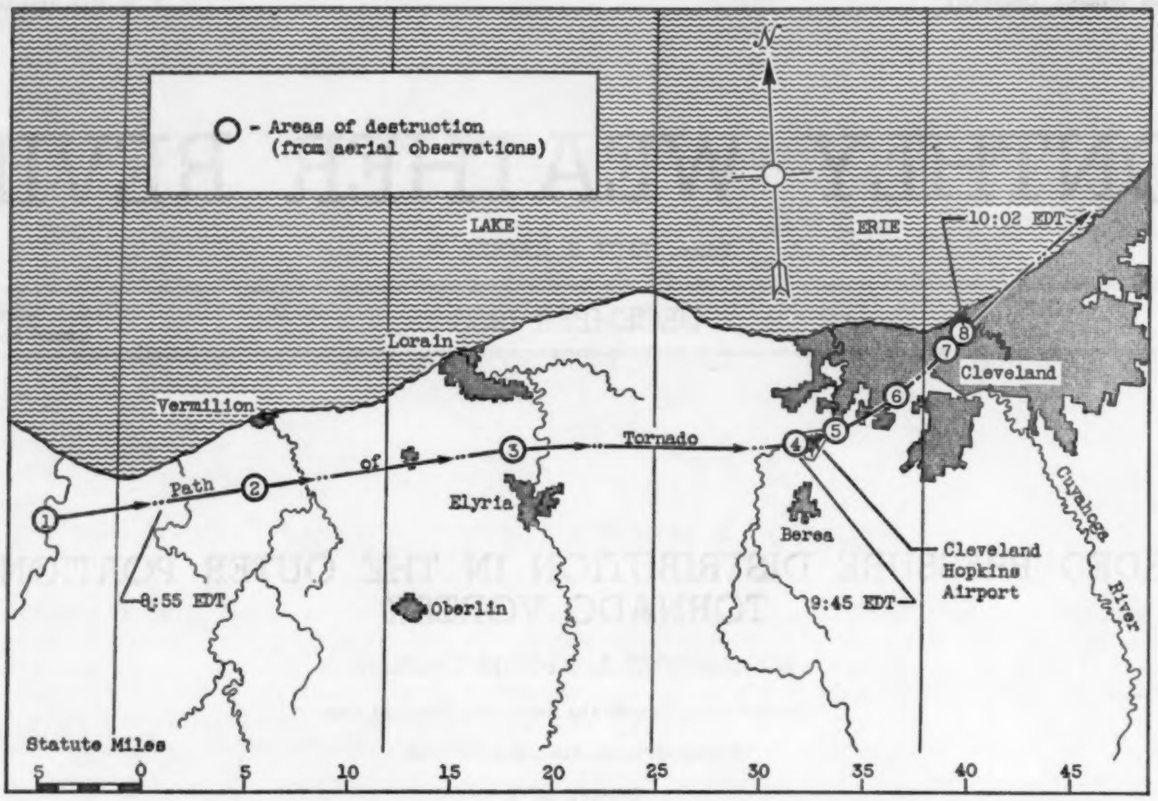

FIGURE 1.—Map of northern Ohio showing path of tornado on June 8, 1953.

of Cleveland. The numbered points along the tornado path indicate all the areas of destruction visible from the air. Other destruction between these points may have occurred. (Ground strikes were difficult to observe over open farming country west of the Airport). However, it was apparent that the center of the tornado skipped over considerable distances along the path.

Because of the large intervals between points of observed damage, the possibility exists that more than one tornado was involved. However, the facts that all the visible areas of damage could be connected by a reasonably smooth curve and that the time of observation at three points (as shown in fig. 1) indicated a nearly uniform speed of about 35 m. p. h. support the hypothesis that only a single tornado occurred. On the other hand, the western extremity of the tornado path may have been farther west than plotted on the map of figure 1. Damage was reported as far west as Bowling Green, Ohio, which is over 90 miles from the Cleveland Airport. Bowling Green is approximately on a straight line extension of the east-west tornado path plotted in figure 1. The aerial survey did not extend beyond the first point on the map.

METEOROLOGICAL DATA

Barograph records.—Barograph traces showing the passage of the tornado were obtained from eight instruments at the Lewis Laboratory located at the points shown on the detailed map in figure 2. The approximate path of the tornado center and the location of points where damage occurred are also shown in figure 2. One additional barogram (from outside the area of fig. 2) was obtained from the Weather Bureau Airport Station located across the Airport about 1.3 miles east of the laboratory.

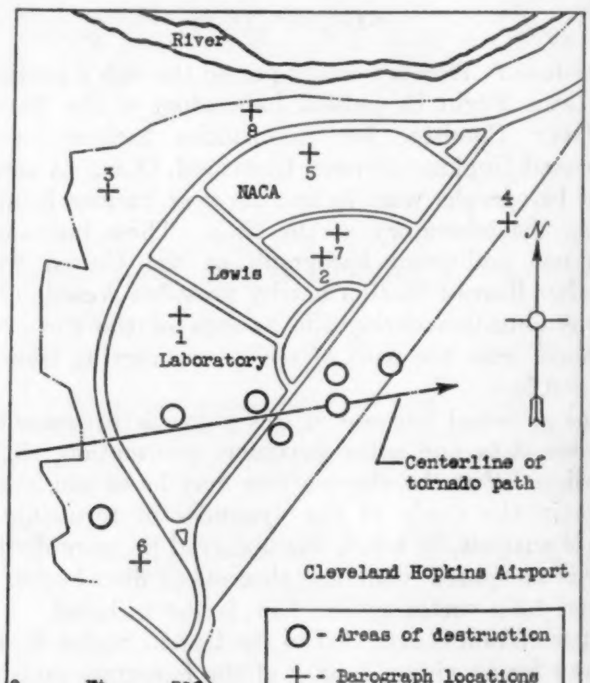

FIGURE 2.—Path of tornado of June 8, 1953, across NACA Lewis Laboratory in relation to areas of destruction and barograph locations.

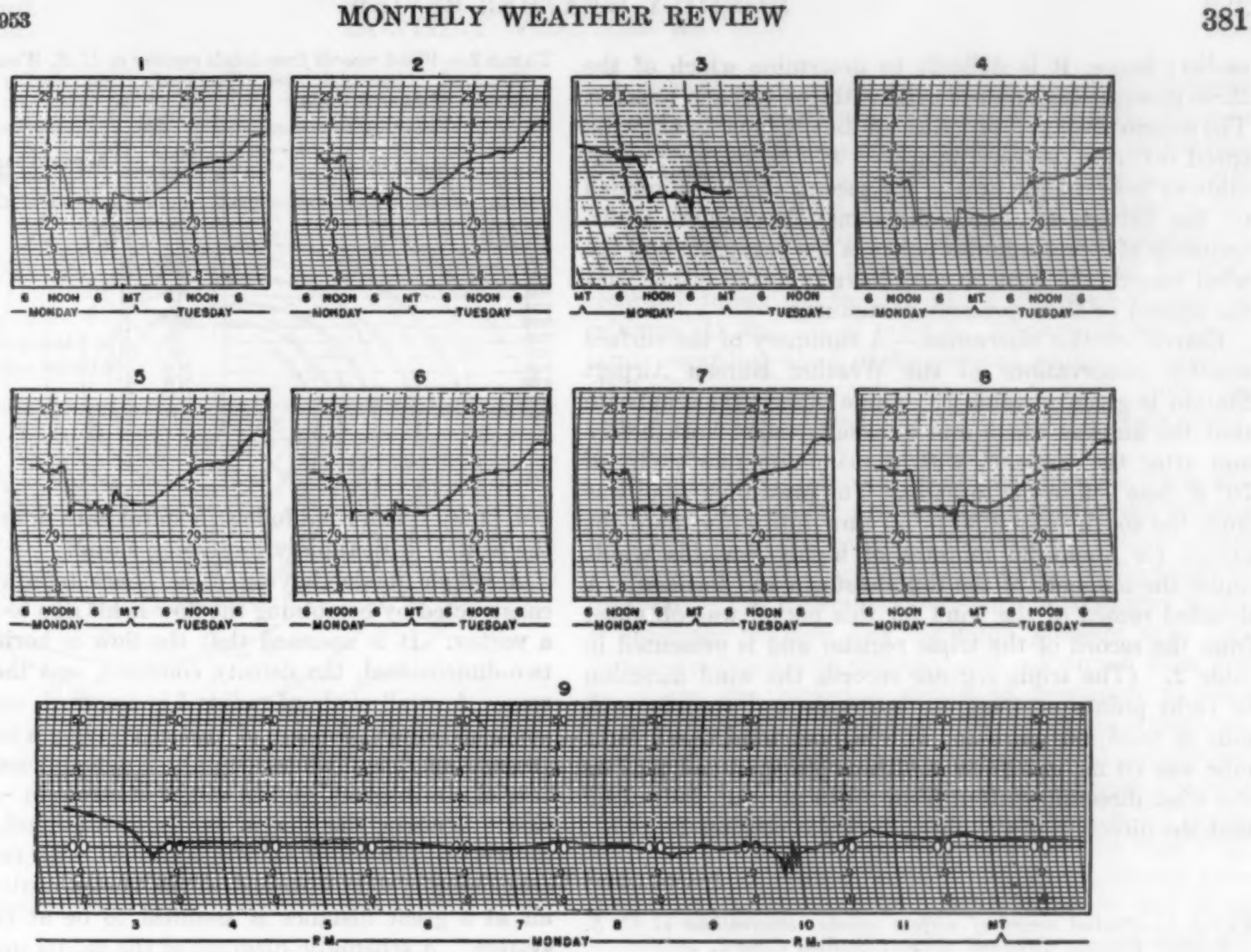

FIGURE 3.—Barograph traces recorded during passage of tornado of June 8, 1953. (Barograms 1-8 at NACA Lewis Laboratory; barogram 9 "fast-run" at Weather Bureau Airport Station.)

The nearest approach of the tornado to the Weather Bureau Station was estimated at about 2,300 feet to the north-northwest. Copies of the barograms are reproduced in figure 3. Station identification numbers from 1 to 8 were assigned to the NACA barograph locations as shown in figure 2, and the Weather Bureau Station barograph was designated as station 9.

As would be expected, the barograms from the eight NACA instruments are nearly identical except for the extent of the pressure drop during the tornado. All the records show a rapid fall in pressure in the early afternoon, amounting to 6 millibars in about an hour. This fall was quickly followed by a slight rise, after which the pressure remained fairly steady until about 7 p. m. EDT. The pressure was unsteady from 7 to 9:30 p. m. followed by a sudden fall as the tornado approached. After the passage of the tornado, the pressure rose steadily for about 45 minutes and then fell slowly to a steady, flat minimum about five hours after the storm.

If it is assumed that nearly all of the pressure change associated directly with the tornado passage occurred within a mile of the center, the pressure fall and recovery took place in less than 4 minutes, since the speed of the tornado was about 35 miles an hour. The time scale of the NACA barographs is approximately $\frac{1}{16}$ inch per hour; hence, the chart movement during the tornado passage was less than 0.005 inch. The traces indicating the fall and rise due to the tornado, therefore, should be practically coincident on the barograms. An examination of the traces reveals, however, that the passage of the tornado was recorded not by a single vertical line but rather by a narrow Y-shaped curve. The interval between the time when the pressure began to fall and when it had returned to the original value was about ½ hour, indicating that the tornado vortex was located within a small-scale trough or low-pressure area about 15 to 20 miles across. Other cases of the occurrence of local low-pressure areas around tornadoes have been reported by Brooks [1].

The barogram from the Weather Bureau Airport Station (No. 9, fig. 3), which was obtained with a much higher chart speed, also shows a period of reduced pressure lasting about half an hour. Instead of a single pressure minimum, this trace shows three distinct minima (about 4 minutes apart) one of which was probably due to the tornado, the others being associated with the thunderstorm. The exact time at which the tornado passed the Weather Bureau Station is in doubt because the station clocks had been stopped by power failure a few minutes

earlier; hence, it is difficult to determine which of the three pressure minima occurred with the tornado passage. The anemometer record indicates that the maximum wind speed occurred between 9:56 and 9:57 p. m. EDT, about midway between the time of the second and third minima on the barogram. Since there may have been a discrepancy of 2 or 3 minutes between the barogram and the wind record, the tornado may have occurred either with the second or third pressure minimum.

General weather observation.—A summary of the surface weather observations at the Weather Bureau Airport Station is given in table 1. These observations indicate that the air was warm and unusually moist both before and after the tornado, with a maximum dew point of 70° F. just before the tornado. The prevailing wind was from the south from 3:30 p. m. EDT until after midnight except for about 30 minutes of highly variable winds under the influence of the thunderstorm and tornado. A detailed record of the wind for this period was obtained from the record of the triple register and is presented in table 2. (The triple register records the wind direction to eight points at 1-minute intervals and records each mile of wind movement.) The highest wind speed for 1 mile was 60 m. p. h., recorded between 9:56 and 9:57 as the wind direction shifted from south to west, indicating that the direction of the circulation was counterclockwise.

TABLE 1.—*Partial record of surface weather observations at U. S. Weather Bureau, Cleveland Airport Station, June 8, 1953*

Time (p. m. EDT)	Temperature (° F.)	Dew Point (° F.)	Winds		Weather and remarks
			Direction	Speed (m. p. h.)	
12:26	81	65	SSW	13	
1:27	82	64	SSW	17	
2:26	79	65	WSW	10	
3:27	78	66	S	22	Gusts to 27.
4:28	83	69	S	20	
5:27	85	68	S	11	
6:25	85	67	S	17	
7:27	82	67	SSW	12	
8:23	80	69	S	15	Light rain shower.
8:50			S	15	Thunderstorm.
9:04			SSE	10	Thunder and moderate rain shower.
9:24*	78	70	S	10	Thunder and moderate rain shower.
9:37*			NE	10	Thunder and heavy rain shower.
9:53*			E	30	Gusts to 65 tornado N end of field 2050 EST moved ENE.
10:02*			S	4	Thunderstorm.
10:25*	78	60	SSW	13	Thunderstorm.
11:27*	75	67	S	5	

*Observation time uncertain due to failure of station clock.

TABLE 2.—*Wind records from triple register at U. S. Weather Bureau, Cleveland Airport Station, Cleveland, Ohio, during passage of tornado of June 8, 1953*

Time (p. m. EDT)	Wind direction (8 points)	Approximate average wind speed (m. p. h.)
9:35–9:38	SE	6
9:39–9:50	NE	14
9:51	NE	
9:52	NE	25
9:53	NE	
9:54	E	
9:55	SW	
9:56	S	60 (fastest mile)
9:57	W	
9:58	NW	50 (fastest 5 minutes)
9:59	NW	
10:00	NW	
10:01–10:05	SW	25

ANALYSIS

Calculation of pressure distribution in model tornado flow field.—The records of minimum pressure from the various barograph locations may be used to define a portion of the pressure profile of the tornado. It is of interest to compare this observed pressure profile with a theoretical pressure-distance relationship calculated for a simple model of a flow pattern having some of the characteristics of a tornado. The winds at ground level in a tornado have been observed to consist of both in-flow and circulation [2, 3]. The wind follows a spiral path in approaching the center, with rapidly increasing speed.

A simple model having these characteristics may be constructed by combining the flow fields due to a sink and a vortex. It is assumed that the flow is horizontal and two-dimensional, the density constant, and the viscosity zero. A small circle of radius δ is assumed, containing a symmetrical distribution of vorticity giving a total vortex strength of Γ, and containing also a symmetrical distribution of convergence giving a sink of strength $-Q$. Outside this circle, the flow is steady, irrotational, and nondivergent. The flow field is described with respect to a coordinate system attached to the vortex center, and the air at a great distance is assumed to be at rest in this system. A schematic diagram of the model tornado flow field is shown in figure 4. The velocity is given by

$$V_t=\Gamma/2\pi r \qquad (r>\delta) \tag{1}$$

$$V_r=-Q/2\pi r \qquad (r>\delta) \tag{2}$$

where V_t and V_r are the tangential and radial velocity components and r is the distance from the center. The magnitude of the resultant velocity V is given by

$$V=\frac{\sqrt{\Gamma^2+Q^2}}{2\pi r} \qquad (r>\delta) \tag{3}$$

Equation (3) shows that the product of the wind speed and the radius is a constant when r is greater than δ; thus,

$$Vr=C=\frac{1}{2\pi}\sqrt{\Gamma^2+Q^2} \qquad (r>\delta) \tag{4}$$

where the constant C is proportional to the resultant strength of the sink and vortex. Using the subscripts 1 and 2 to represent conditions at two arbitrarily chosen points for which $r>\delta$, the application of Bernoulli's equation gives:

$$\frac{1}{2}\rho V_1^2+p_1=\frac{1}{2}\rho V_2^2+p_2 \qquad (r>\delta) \tag{5}$$

where p is the pressure and ρ the density. From equations (4) and (5) is obtained

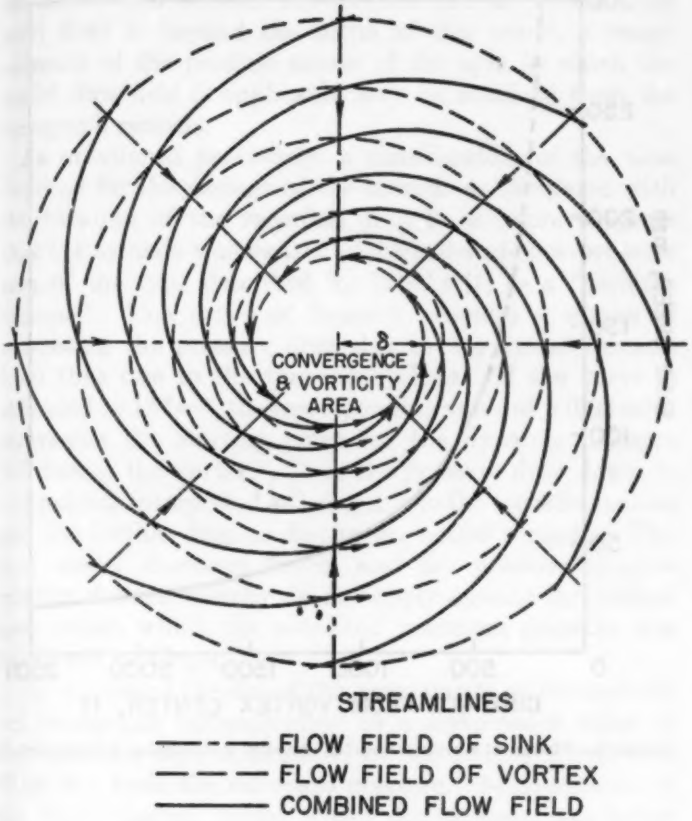

FIGURE 4.—Schematic diagram of model-tornado flow field.

$$\frac{1}{2}\rho\left(\frac{C^2}{r_1^{\,2}}-\frac{C^2}{r_2^{\,2}}\right)=p_2-p_1$$

and solving for C,

$$C=\sqrt{\frac{2(p_2-p_1)}{\rho\left(\frac{1}{r_1^{\,2}}-\frac{1}{r_2^{\,2}}\right)}}\qquad (r>\delta)\qquad (6)$$

Equation (6) shows that the model flow field is characterized by a linear relation between p and $1/r^2$ and that the constant $C=Vr$ may be evaluated from the slope of the line representing p as a function of $1/r^2$.

Equations similar to equation (6) have been used by Williams [4] to describe the pressure distribution in dust whirls and by Deppermann [5] in a discussion of typhoons. A similarity is also noted between the model flow field shown in figure 4 and the pattern of trajectories relative to the moving center of a tropical cyclone as determined by Hughes [6] from flight observations of the wind at 1,000 feet altitude.

Comparison of observed and calculated pressure distribution.—In order to compare the observed pressures with the pressure distribution calculated for the model flow field, it is necessary to refer the observed pressure minima to a common base, because of differences in elevation and instrument settings. Since the tornado occurred during the passage of a thunderstorm, the unsteady pressure occurring just before or after the passage of the tornado does not provide a suitable reference. An examination of the barograms indicated that the flat pressure minimum which occurred about 5 hours after the tornado would provide a suitable reference pressure. The uncorrected values of reference pressure and minimum pressure recorded during the tornado at all stations are listed in columns (1) and (2) of table 3. Because of the uncertainty regarding which of the pressure minima at station 9 (WBAS) was associated with the tornado, both the second and third minima (designated b and c, respectively, in table 3 and fig. 5) were measured.

The measured values of minimum pressure were corrected for differences in elevation and instrument settings by assigning to the reference pressure a standard value of 985 millibars (the approximate average of the observed readings). The differences between the measured values of reference pressure and minimum pressure were converted from inches to millibars and subtracted from 985 to obtain the corrected values of minimum pressure listed in column (3) of table 3. The accuracy of measurement of the barograph traces (using an optical comparator) was about ± 0.002 inch, and the maximum possible error due to ignoring air density differences in the reduction to a standard reference pressure was less than 0.001 inch; hence, the overall accuracy of the minimum pressure values is about ± 0.1 millibar if errors due to incomplete response of the instrument and buildings are neglected.

TABLE 3.—*Data on minimum pressure and distance from tornado path for 9 barograph stations*

Station no.	(1) Uncorrected reference pressure (in. Hg.)	(2) Uncorrected minimum pressure (in. Hg.)	(3) Corrected minimum pressure (mb.)	(4) Distance from path center, r (m.)	(5) $1/r^2\times 10^6$ (m.$^{-2}$)
1	29.090	28.860	977.2	233	18.4
2	29.116	28.939	979.0	280	12.7
3	29.115	29.020	981.8	485	4.2
4	29.025	28.833	978.45	271	13.6
5	29.121	29.022	981.65	471	4.5
6	29.092	28.838	976.4	−218	21.0
7	29.104	28.979	980.75	320	9.9
8	29.116	29.030	982.1	580	3.0
9 (b)	29.008	28.903	981.95	−*750	2.0
9 (c)	----	28.932	982.45	----	----

*Estimated.
(b) Second minimum.
(c) Third minimum.

In addition to the pressure data the distance from each station to the center line of the tornado path is required. The direction of the path at the laboratory was determined by constructing an arc of a circle through points 4, 5, and 6 on the map of figure 1. A trial line having the direction of the tangent to the arc at point 4 (the Lewis Laboratory) was drawn on a detailed map of the laboratory, passing about half way between barograph stations 1 and 6, and the perpendicular distance from each station to this line was measured. The final position of the line defining the path (fig. 2) was established by shifting the trial line

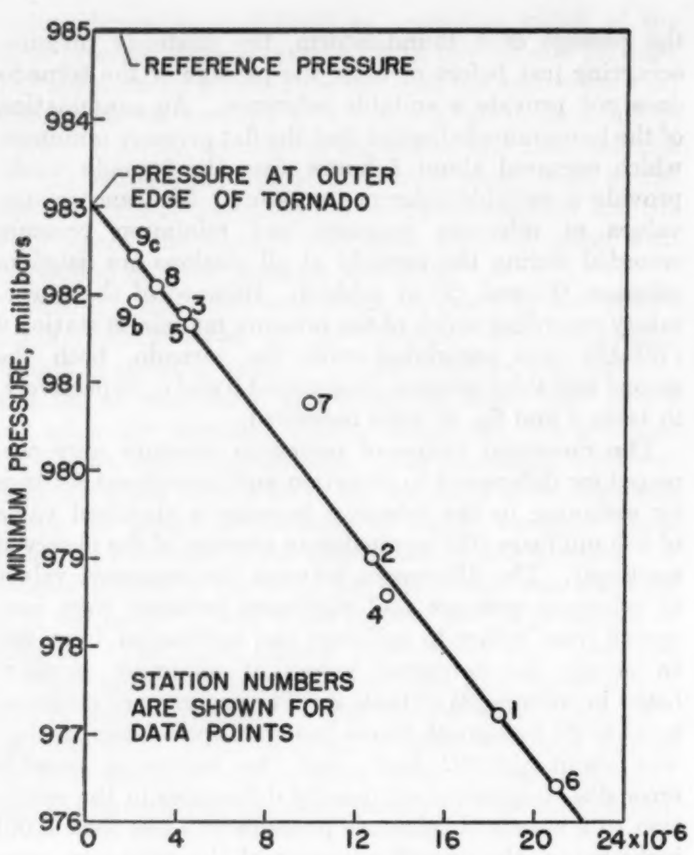

FIGURE 5.—Minimum pressure during tornado passage as a function of the reciprocal of the square of the distance from the path of the center, $1/r^2$ where r is distance from tornado path.

without changing its direction until a position was obtained such that the point representing barograph station 6 (the only station southeast of the path) on a plot of minimum pressure as a function of $1/r^2$ fell on the line determined by the other stations. As shown in figure 2, the storm path located in this way passes close to the areas where damage occurred. It should be noted that the locations of damage are determined by the locations or structures susceptible to wind damage as well as by the storm path.

Values of distance r from the path and $1/r^2$ are listed in columns (4) and (5) of table 3. The relation between minimum pressure and $1/r^2$ is shown in figure 5. The close grouping of the data points about a straight line indicates that the observed pressure distribution is in good agreement with the calculated distribution over the range of distance covered by the observations. It should be noted that the point representing station 6 was "forced" to fall upon the line because of the method used to locate the path of the center.

A measure of the intensity of the tornado, represented by the constant $C=Vr$, was calculated from equation (6) using the slope of the curve of figure 5, and taking the air density as 0.0114 decigram per cubic centimeter.

$$Vr=7.5\times10^3 \text{ m}^2/\text{sec} \qquad (7)$$

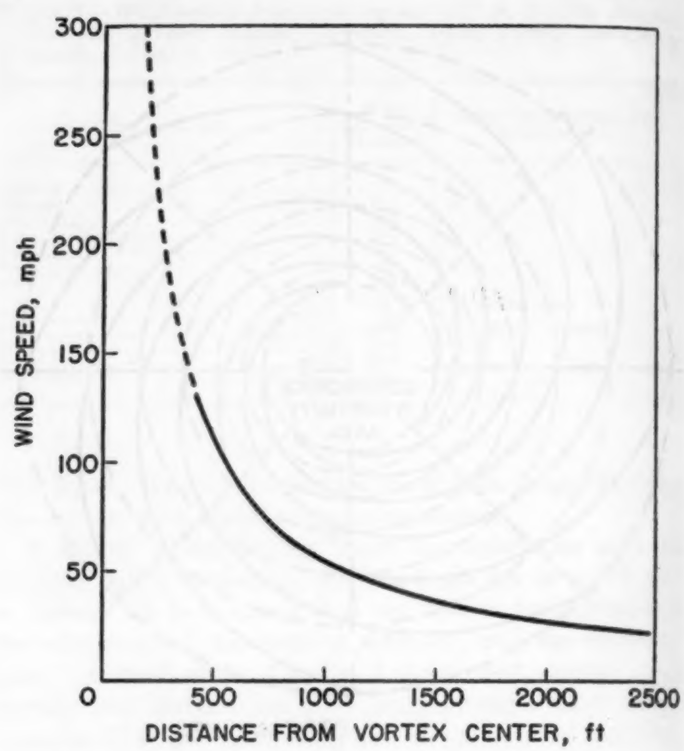

FIGURE 6.—Wind speed in tornado model as a function of the distance from the center.

If the speed is expressed in miles per hour and the radius in feet, the constant is 5.5×10^4 m. p. h.-ft. The velocity distribution corresponding to this value of Vr is shown in figure 6.

DISCUSSION

The entire model flow field is to be regarded as moving with respect to the ground with the velocity of the center; thus, the velocity distribution shown in figure 6 applies to a moving coordinate system attached to the tornado center. The wind speed with respect to the earth is increased on the right side and reduced on the left side because of the movement of the storm. For example, the wind speed with respect to the moving coordinate system indicated in figure 6 for the Weather Bureau Station at about 2,300 feet from the center is 24 m. p. h. When this value is added to the speed of movement of the storm, which averaged about 35 m. p. h., the result (59 m. p. h.) agrees satisfactorily with the reported maximum wind speed of 65 m. p. h. (table 1). Although no wind measurements are available from the left side of the tornado, an observer, located indoors at station 8, reported that the tornado was visible and clearly audible but no unusually high winds occurred at that time though strong and gusty winds had occurred a short time previously.

Since the velocity of a tornado is generally not the same as that of the surrounding surface air and the model does not provide for relative motion of the tornado in its environment, the moving model represents the actual wind only over a limited area. Although a discussion of

the interaction between the tornado and the surrounding wind field is beyond the scope of this paper, a rough estimate of the possible extent of the area in which the model flow field is applicable may be obtained from the barograph records.

As mentioned previously, a consideration of the time required for the passage of the tornado as compared with the duration of the recorded drop in pressure suggests that the tornado was located in a small-scale low-pressure area of the type described by Brooks [1] as a "tornado cyclone". The curve of figure 5 provides a means of separating the pressure drop due to the actual tornado from that due to the tornado cyclone. If the curve is extended to $1/r^2=0$, the corresponding value of p (983 mb.) represents the starting point for the dynamic pressure fall due to the vortex. Thus the pressure drop down to this point is interpreted as being due to the tornado cyclone and the further drop as due to the actual tornado. The flow model discussed herein and the pressure-distance relation defined thereby do not apply outside the limited area within which the corrected minimum pressure was below 983 millibars.

To determine the size of this area, points on the individual barograms corresponding to a corrected-p value of 983 millibars were determined by subtracting 2 millibars (0.06 in.) from the reference pressure. Measurement of the time interval during which the pressure was below this value gave results ranging from 5 to 11 minutes, the average being 8 minutes. Since the speed of the tornado was about 35 m. p. h., a duration of 8 minutes corresponds to the passage of an area slightly less than 5 miles in diameter. It may be concluded, therefore, that the model flow field does not apply at a distance of 2½ miles or more from the center. The data from figure 5 indicate that the model is applicable over the range of the observations, or out to a radius of nearly ½ mile. Thus, the transition zone between the model flow field and its environment apparently occurs somewhere in the range between ½ mile and 2½ miles from the center.

The range of applicability of the model flow field is also limited in the central area of the tornado because the equations are based on the condition that r must be greater than δ. Within the central core of radius δ, the convergence and vorticity are no longer negligible; the product Vr is no longer constant but decreases with decreasing r; and the pressure falls less rapidly than equation (6) would indicate. As shown by equation (4), the radius of the circle of maximum wind speed cannot be greater than δ; hence, the maximum wind speed must be located within the core.

In the case of this particular tornado, the radius of the core was apparently less than the distance to the nearest barograph (720 ft.) since the pressure variation at that distance was in accordance with the irrotational model. It is evident from the pattern of damage (fig. 2) that the radius of the circle of maximum wind speed was much less than 720 feet, probably being of the order of 100 to 200 feet. Therefore, the radius of the core δ, which marks the inner limit of applicability of the model flow field, was probably between 200 and 700 feet.

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SINGULARITIES IN WEATHER AT WALLA WALLA, WASH., AS RELATED TO THE INDEX OF ZONAL WESTERLIES

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[Manuscript received July 20, 1953; revision received October 26, 1953]

ABSTRACT

The concept of primary singularities extant in the general circulation, and their relation to secondary singularities in local and regional weather are examined through analysis of the Walla Walla, Wash., daily records of January temperature and June precipitation. The results underline the influence of the hemispheric circulation upon local weather.

INTRODUCTION

The traditionally accepted January thaw in New England and elsewhere on the east coast holds a strong place in the folklore. Slocum [1] in a study of temperature records for Washington, D. C., and Wahl [2], in investigating the New England thaw within the Boston records, presented results that bear on the question of the existence of such a singularity. Both of these studies point up the anomalous warming on the east coast for the period January 20–23. That this tendency is aligned with a change in the synoptic conditions was shown by Wahl with mean maps for the 20th and 27th of January which delineated a change from a westerly circulation pattern to one predominantly northwesterly.

A further stride forward was made by Wahl [3] in a second paper in which the January thaw was related to the mean features of the general circulation by judicious application of the total zonal index of the westerlies to the Boston records. The existence of primary singularities, representing distinct changes in the hemispheric flow pattern and affecting the local or secondary singularities, was reflected in the monthly mean index. It was found that separation of the Boston record into high and low index years led to mean temperature curves with pronounced accentuation of the thaw in the specific low-index singularity curve.

In view of these interesting results it was decided to examine the daily maximum temperature during January and precipitation occurrences during June at Walla Walla, Wash., for evidence of such a primary-secondary singularity relationship in this region. The local climatological conditions suggested that the maximum temperature is more representative of the air-mass regime here than is the mean.

JANUARY TEMPERATURE SINGULARITIES

At first, the entire period of record from 1886–1950, during which radii of site changes were small, was ex-

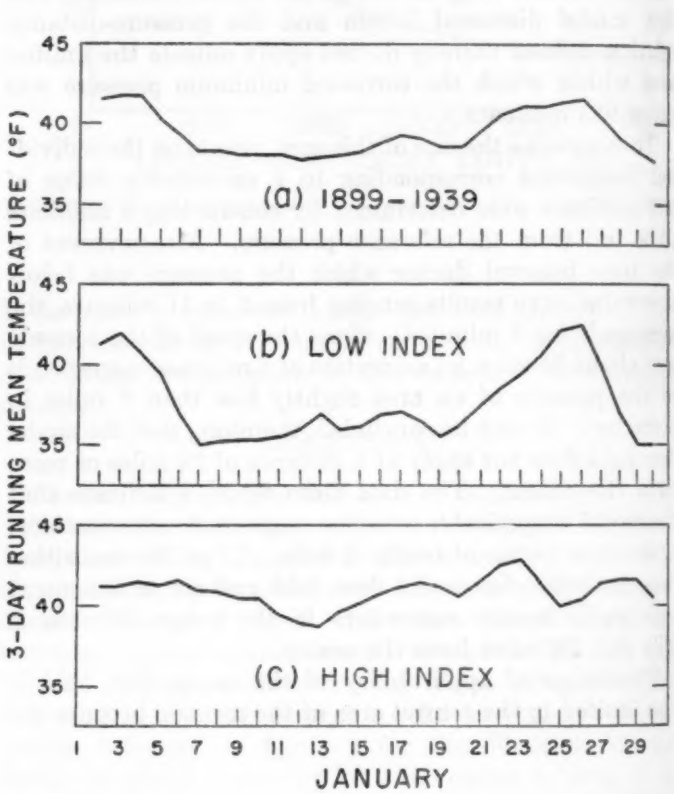

FIGURE 1.—Three-day running mean daily maximum temperatures, Walla Walla, Wash., for January: (a) from 41 years record (1899–1939), (b) from low-index months (20 yr.), (c) from high-index months (21 yr.)

pressed as 3-day running means of daily maximum temperature for January. However, in this paper attention is limited to the 3-day means for the interim period of 1899–1939, the main features of which are similar to the long-term record. This limitation was imposed because the hemispheric zonal indices were available for only the shorter period. The median value of the mean zonal index served as the separation point for the arbitrary division of the period into high and low index years. All those years below the median were taken as low index years, with the remainder ascribed as high index. For each class

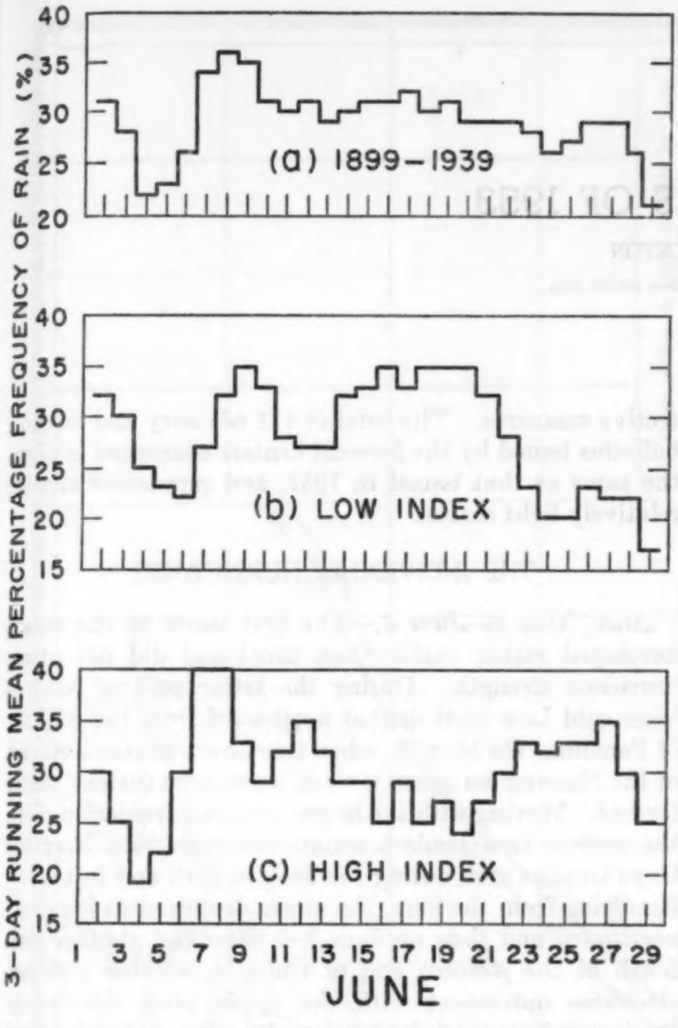

FIGURE 2.—Three-day running mean daily rainfall frequency (%), Walla Walla, Wash., for June: (a) from 41 years record (1899-1939), (b) from low-index months (20 yr.), (c) from high-index months (21 yr.).

3-day running means were derived. Figure 1 shows the results of these derivations.

It is noted in figure 1 that a definite filtering effect is obtained within the index curves. The long-term curve displays a cooling as the month opens which, with but minor rises and falls, continues until January 20. Marked warming then occurs, especially January 23–26, after which steady cooling is manifest at month-end. Both warmer periods are given pronounced delineation by the low index curve at opposite ends of the month. In contrast, cooling is shown for January 23–26 in the high index graph. The smoothness of the high index curve and other features that contrast with the low index curve are in general accord with expectations from synoptic reasoning. For example, the mean map for the entire northern hemisphere for January 26 [4] shows low index conditions in the Pacific as well as in the Atlantic with a double-celled Aleutian Low and pronounced southwesterly flow from the warmer ocean surfaces.

The singularity curves at Walla Walla are substantiated by a curve of maximum temperature at Portland, Oreg., which exhibits a similar pattern (Wahl, unpublished).

JUNE PRECIPITATION SINGULARITIES

An investigation was then made of the Walla Walla records for the frequency of precipitation occurrence in June, the last month of appreciable rainfall for the ripening winter wheat of this region. Again 3-day running means were obtained. The series was smoothed by giving half-weight to days with trace amounts. The smoothed means expressed as percentage frequency of occurrence are shown in figure 2.

These curves for June occurrence of rain at Walla Walla show a type behavior somewhat paralleling the so-called monsoon burst of Europe. It is at once apparent that the first maximum is a high index singularity, the second a low index feature, thus giving rise to apparent alternate dates, either late or early rain according to the index pattern in a specific year.

In addition to the two investigations described above, attempts using more regional indices to characterize the circulation west of the test area were made. However, consistent with Wahl's results for Boston, only less marked separation of the different singularity types was observed.

CONCLUSIONS

The results of this study underline the influence of the hemispheric circulation upon the local behavior of the weather elements, and thus may serve as additional evidence for the value of such local investigations in questions concerning the mechanism of the general circulation.

ACKNOWLEDGMENTS

I am indebted to the Whitman College Library for use of their facilities; to L. D. Vaughan for loan of basic reference material; to E. W. Wahl of the Air Force Cambridge Research Center for much material, invaluable comment, and most of all for the intellectual impetus of his research on a highly provocative problem.

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HURRICANES OF 1953

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GENERAL SUMMARY

The hurricane season of 1953 was about normal in the number of storms, with a total of eight. Four reached the coast of the United States, but only two of them were of hurricane force and these were not particularly severe. This resulted in only one death and damage estimated at about $6,000,000. Hurricane Carol did $1,000,000 damages to fishing craft along the New England coast and caused some destruction in the Canadian Provinces of Nova Scotia and New Brunswick. Edna caused quite a lot of damage at Bermuda, but no dollar estimates have been received.

In addition to the wind damage, storm Hazel, that crossed southern Florida October 9, produced heavy rains which added to the flooded conditions in the river valleys of central and northeastern Florida, but it was not possible to separate damage by the storm rains from the floods already existing from previous rains. The overall flood damage, principally in the Peace, Kissimmee, and St. Johns River Valleys, has been estimated at between 9 and 10 million dollars. In the upper St. Johns Valley, the flood was the worst of record, and Hazel was responsible for the last foot or two of the rise.

Six of the storms, Barbara, Carol, Dolly, Edna, Florence, and Gail, were of hurricane force at some time in their courses, while Alice and Hazel were less than hurricane force, but there seemed to be a general lack of sustaining power, and none of the storms was outstandingly violent. Several gained hurricane force for a time only to lose it while at sea, without apparent reason. Carol developed the strongest wind (estimated about 130 knots) while passing north of the Leeward Islands and Puerto Rico, but began to weaken by the time it reached the latitude of Bermuda. Another feature of this season's storms was their rather pronounced meridional movement which can be seen from a glance at the track chart (fig. 1). This shows the predominantly northerly movement, or recurvature at rather low latitudes, and the lack of westward zonal movement, especially west of Longitude 60° W; hence, no storm reached the western Gulf of Mexico during the season.

The warning and advisory service was of a high order and all land areas affected had ample warnings of the approaching storms. This doubtless reduced damages and casualties by allowing time for evacuations and protective measures. The total of 111 advisory and warning bulletins issued by the forecast centers concerned is about the same as that issued in 1952, and represents another relatively light season.

THE INDIVIDUAL HURRICANES

Alice, May 25–June 6.—The first storm of the season developed rather earlier than usual and did not attain hurricane strength. During the latter part of May, a large cold Low aloft drifted northward from the vicinity of Panama. On May 25, when this Low was centered east of the Nicaraguan coast, a weak warm-core surface center formed. Moving with the larger cyclonic circulation aloft, the surface Low made a counterclockwise loop over the Cape Gracias area during the 26th to 28th and lost force. Emerging from the loop, the storm deepened as it moved northward and then on June 1–2 described another loop north of the western end of Cuba in another counterclockwise movement with the upper level circulation. During this second loop, aircraft estimated maximum winds at about 55 knots on June 1, but on the 2d and 3d the wind force dropped to 35–40 knots. Northward movement was resumed on June 4 and maximum development was reached on the 5th when aircraft estimated highest winds to be 60 to 65 knots in brief squalls northeast of the center near 29° N., 83° to 85° W. Central pressure at this time was about 997 mb. (29.44 inches). During the night of the 5th, the storm again lost force and when it moved inland a short distance west of Panama City, Fla., about noon of the 6th, strongest winds were around 35 to 40 knots. There was no damage of consequence in Florida.

This storm gave heavy flooding rains in western Cuba and unconfirmed press reports indicate there were several deaths from drowning. In Cuba, the rains broke a severe drought of nine months duration, and in Florida, the rains were beneficial in breaking a dry spell of much shorter length.

Barbara, August 12–15.—The second storm developed during the night of August 11 northeast of the Bahama Islands from a weak easterly wave that had moved westward over the Atlantic during several days preceding. On the morning of the 12th, reconnaissance aircraft located the center in the formative stages near 29° N., 76° W.; it was moving northward. Strongest winds were about 75 m. p. h. on the northeast side at this time, but the

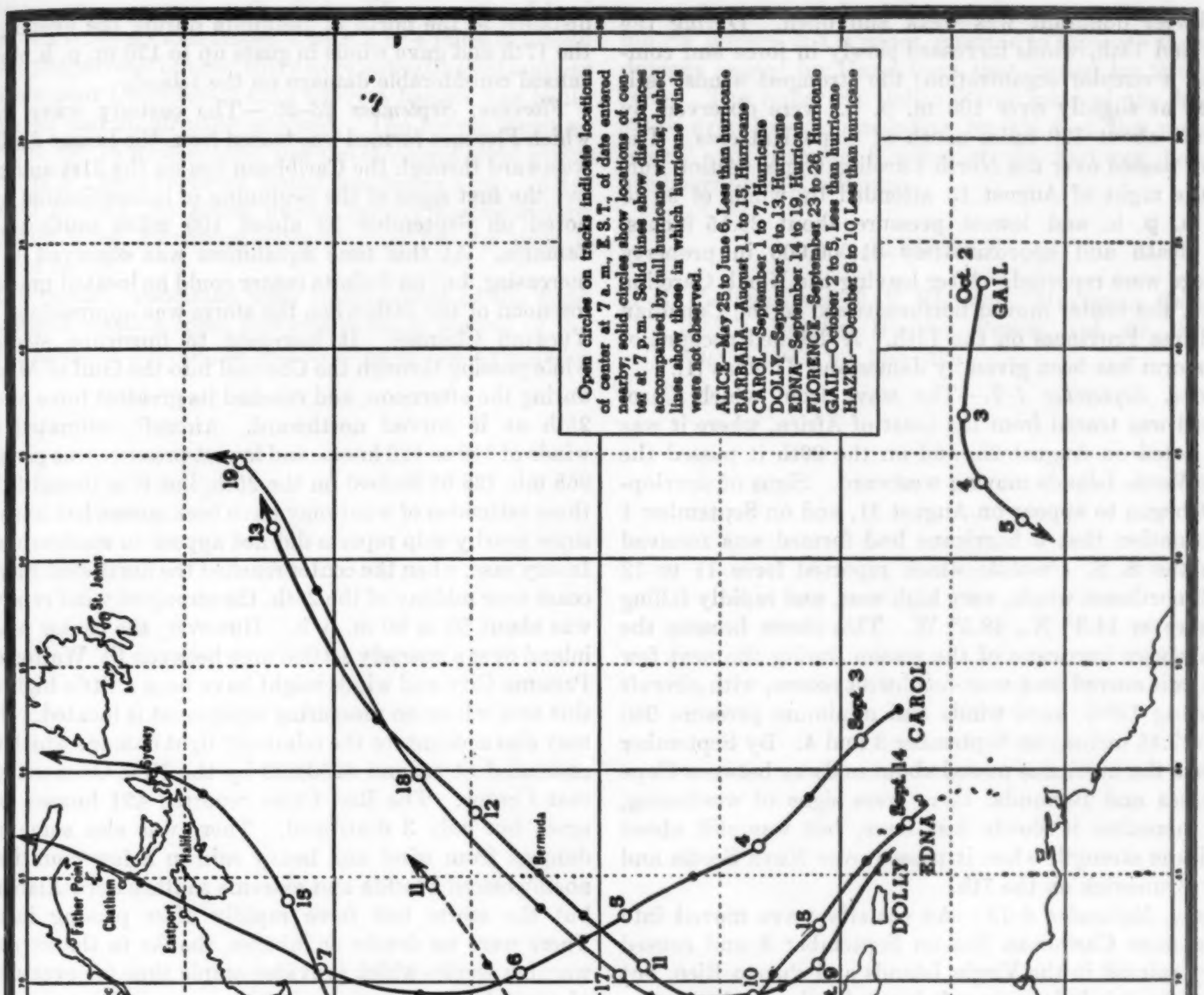

FIGURE 1.—Tracks of hurricanes which occurred during 1953.

southwest quadrant was weak and open. During the 12th and 13th, winds increased slowly in force and completed a circular organization; the strongest winds, estimated at slightly over 100 m. p. h., were observed by aircraft about 120 miles south of Cape Hatteras. The center passed over the North Carolina Capes section during the night of August 13 attended by winds of 90 to 100 m. p. h. and lowest pressure about 29.15 inches. One death and approximately $1,000,000 in property damage were reported. After leaving the North Carolina Capes, the center moved northeastward to the Canadian Maritime Provinces on the 15th. A detailed account of this storm has been given by James and Thomas [1].

Carol, September 1–7.—The wave from which Carol formed was traced from the coast of Africa, where it was first noted on August 28, and on the 29th it passed the Cape Verde Islands moving westward. Signs of development began to appear on August 31, and on September 1 confirmation that a hurricane had formed was received from the S. S. *Umatilla* which reported force 11 to 12 north-northeast winds, very high seas, and rapidly falling pressure at 14.3° N., 48.5° W. This storm became the most severe hurricane of the season during the next few days as it moved on a west-northwest course, with aircraft reporting 130+ knot winds and minimum pressure 930 mb. (27.45 inches) on September 3 and 4. By September 6, when the hurricane passed about midway between Cape Hatteras and Bermuda, there were signs of weakening, and thereafter it slowly lost force, but was still about hurricane strength when it passed over Nova Scotia and New Brunswick on the 7th.

Dolly, September 8–13.—An easterly wave moved into the eastern Caribbean Sea on September 8 and caused heavy rainfall in the Virgin Islands and Puerto Rico, but it was the 9th before aircraft located a developing center in the wave near 21° N., 69° W. The center developed slowly and curved toward a northerly course during the 9th and 10th, reaching maximum development on the 10th when aircraft estimated top wind speed at near 100 knots. Thereafter the storm moved northeastward with waning force, passed over Bermuda the night of the 11th, where only gale winds were experienced, and thence moved rapidly northeastward over the Atlantic during the 12th and 13th beyond the range of reconnaissance aircraft. Little or no damage was caused at Bermuda. This was one of the season's storms that lost force rapidly without apparent cause, after attaining considerable intensity.

Edna, September 14–19.—Following closely behind Dolly, Edna began forming in a squally wave over and to the north of the Leeward Islands on September 14. On the morning of the 15th the center was first definitely located at about 20° N., 66° W. Thereafter the storm strengthened rapidly to a hurricane with strongest wind about 125 m. p. h. and followed a broad curve to north and northeast that very closely paralleled the course taken by Dolly a few days earlier. The center passed a short distance to the north of Bermuda during the evening of the 17th and gave winds in gusts up to 120 m. p. h. which caused considerable damage on the Island.

Florence, September 23–26.—The easterly wave from which Florence formed was traced from the Lesser Antilles westward through the Caribbean Sea on the 21st and 22d, but the first signs of the beginning of intensification were noted on September 23 about 100 miles southeast of Jamaica. At this time squalliness was observed to be increasing, but no definite center could be located until the forenoon of the 24th when the storm was approaching the Yucatan Channel. It increased to hurricane strength while passing through the Channel into the Gulf of Mexico during the afternoon, and reached its greatest force on the 25th as it curved northward. Aircraft estimated top winds of 110 to 120 knots, and lowest pressure was given at 968 mb. (28.65 inches) on the 25th, but it is thought that these estimates of wind may have been somewhat too high since nearby ship reports did not appear to confirm them. In any case, when the center reached the northwest Florida coast near midday of the 26th, the strongest wind reported was about 80 to 90 m. p. h. However, the center passed inland over a sparsely settled area between Ft. Walton and Panama City and winds might have been a little higher in this area where no measuring equipment is located. This may also account for the relatively light damage which was estimated at around $200,000 by the New Orleans Forecast Center. The Red Cross reported 421 houses damaged, but only 3 destroyed. There was also some crop damage from wind and heavy rain in a few counties of northwestern Florida and extreme southeastern Alabama, but the storm lost force rapidly after passing inland. There were no deaths or injuries, thanks to the excellent warning service which provided ample time for evacuation of coastal danger areas.

Gail, October 2–4.—The intensification of an easterly wave was noted on the morning of October 2 near 14° N., 37° W. and on the morning of the 3d, the *S. S. Thorbjorg* passed near the center 400 miles farther west. At 1200 GMT this vessel reported westerly winds at 44 knots and lowest pressure 29.12 inches with rough seas. Maximum winds were estimated at 75 to 80 m. p. h. at the time the ship passed near the center. This observation was made near 15.5° N., 43° W. No definite fixes were obtained thereafter.

Hazel, October 8–10.—The last storm of the season was born in the Yucatan Channel on October 8. It moved northeastward and increased to almost hurricane force by the time it moved into Florida just north of Ft. Myers about 1100 EST of the 9th. Winds up to 60 to 70 m. p. h. attended the storm's northeastward transit of Florida. It passed into the Atlantic near Vero Beach at about 1700 EST of the 9th. Damage was light to moderate, as would be expected from winds of only gale force, and totaled $250,000 or slightly more. One, and possibly two, small tornadoes occurred on the storm's leading edge as it crossed

Florida: one occurred at St. James City on Pine Island west of Ft. Myers and traced a path 3 or 4 miles in length destroying several houses; there were indications of another tornado near Okeechobee City where a hangar was badly damaged and an airplane wrecked. The lowest pressure, 987 mb. (29.15 inches), and also the strongest wind gusts, 80 m. p. h., were reported from Okeechobee City. After leaving Florida, the storm moved rapidly northeastward and lost force, becoming extra-tropical by the time it reached 35° N.

The rainfall associated with Hazel added to the flood conditions existing from previous rains in several of the river valleys of Florida, as well as some of the Everglades area. The overall flood damage is estimated at 9 to 10 million dollars, but it is not possible to separate the flood damage caused by Hazel from that caused by the other rains. The upper St. Johns River reached the highest stage ever known, exceeding by 1½ feet the previous record and covering 6 miles of the highway between Melbourne and Kissimmee.

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THE WEATHER AND CIRCULATION OF DECEMBER 1953[1]

A Month of Fast Westerly Flow

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WAVE PATTERN AND WIND FIELD

The monthly mean circulation pattern at 700 mb. for December 1953 was characterized by four pronounced regions of positive height anomaly at middle and lower latitudes, while large negative centers were located over Greenland and northeastern Canada, the central Pacific, and the southeastern Atlantic (fig. 1). The positive areas were associated with northward extensions into middle latitudes of subtropical high cells in the western Pacific, eastern Pacific, western Atlantic, and the Mediterranean. Except for the European ridge, which was essentially meridional in character, these positive anomaly regions were oriented zonally and overshadowed areas of negative anomaly south of about latitude 50° N. In addition, these areas were arranged in a wavelike pattern with fairly uniform longitudinal spacing, especially between the western Pacific and the central Atlantic. Poleward of latitude 50° N. heights were predominantly below normal, not only in the major troughs over eastern Canada, the central Pacific, and northeastern Siberia, but even in the well-defined ridge over western Canada. Thus at middle latitudes the 700-mb. contours formed a broad cyclonic pattern over wide longitudinal zones from eastern Asia to the eastern Pacific and from central North America to the central Atlantic.

These features of the mean 700-mb. chart compose what is usually termed a typical high index circulation pattern. Figure 2A portrays the simple nature of this broad westerly flow from eastern Asia into the central Atlantic. In general, over a large part of the hemisphere there was a single, well-defined axis of maximum wind speed which did little meandering. It was only over the eastern Atlantic and Europe that a pronounced split in the basic current was observed. The strongest winds were located over the Pacific in association with the deep Aleutian Low and central Pacific trough (fig. 1). In fact, the maximum speed center was located just slightly to the rear of this major trough at latitude 40° N. in a long, zonally oriented belt of strong winds exceeding 16 m/sec which stretched clear across the ocean from Korea to near the coast of Washington. A similar belt of winds in excess of 16 m/sec extended from the Mississippi River eastward to the central Atlantic and thence northeastward to the vicinity of Iceland. The maximum speed center southeast of Newfoundland was located due south of the abnormally deep cyclone center at the southern end of Greenland.

Figure 2B reveals in striking fashion the considerable anomaly of the 700-mb winds during the month. Most sections of the hemisphere north of 35° N. experienced mean wind speeds in excess of normal. The greatest positive anomalies were located in northeastern sections of both the Pacific and the Atlantic. While wind speeds over the North American continent were weaker than over the oceans on both an absolute and relative basis, they were predominantly above normal. Probably of most direct significance to the weather of the United States during the month were the stronger-than-normal westerlies which struck the Pacific Coast from British Columbia to Oregon, crossed the northern Rockies into the Northern Plains, and then fanned out into a more diffuse stream over the central United States (figs. 1 and 2). Other abnormally strong winds over the United States were observed from the lower Mississippi Valley northeastward to New England. This axis of positive wind anomaly lay some 10° of longitude to the east of, and virtually parallel to, the central United States trough.

It is interesting to note that December 1953 was the eighth consecutive month during which the temperate westerly (35°–55° N.) index at 700 mb. for the Western Hemisphere was higher than normal. The period from the second half of November through December represented the culmination of this abnormality as index values reached a maximum anomaly of +2 m/sec. It is also noteworthy that the general character of the circulation throughout this period of maximum index (i. e., from mid-November through December) remained essentially fixed. This can be seen by comparing figure 1 with figure 1B of last month's article [1]. It was shown there how the circulation during the second half of November represented a large break from the prevailing flow of the first half of the month. December's circulation pattern resembled that of November 16–30 in almost every detail except that the southern end of the Pacific trough progressed from western to central sections of the ocean and a slight increase in wave amplitude took place.

[1] See Charts I-XV following p. 404 for analyzed climatological data for the month.

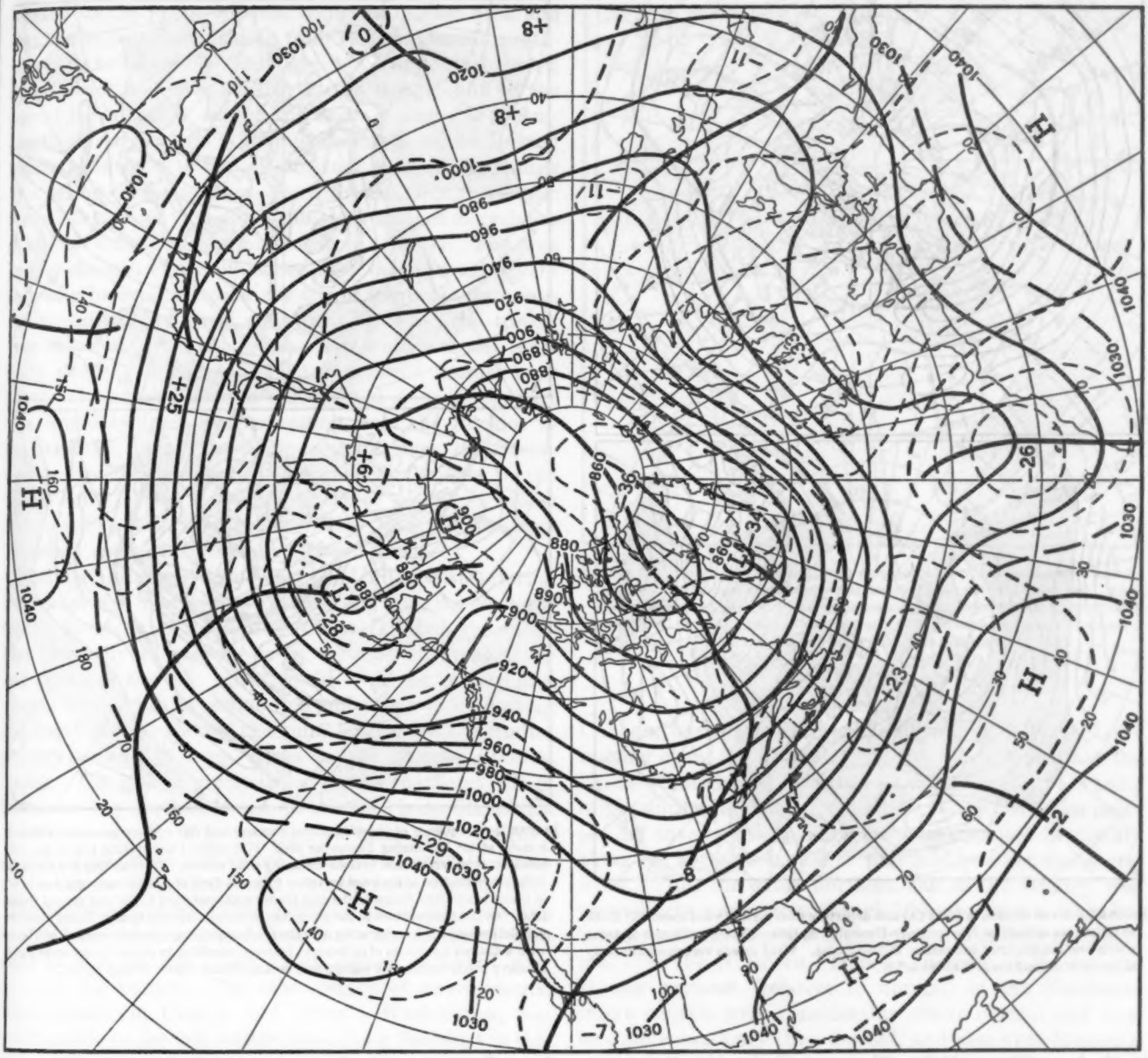

FIGURE 1.—Mean 700-mb. chart with height contours and departures from normal (both labeled in tens of feet) for November 29–December 28, 1953. Below-normal heights prevailed north of latitude 50° N. while positive anomalies were dominant in the subtropical ridges from eastern Asia eastward to the central Atlantic.

Thus a nearly steady-state circulation over virtually the entire hemisphere accompanied the sustained high index of the last month and a half of 1953.

RELATED CYCLONE TRACKS, FRONTS, AND PRECIPITATION

Fast westerly flow had a decided effect on the tracks of cyclones in the North American region during December. The outstanding storm track, along which storminess was extremely frequent, extended from the Gulf of Alaska eastward across southern Canada and thence northeastward to the Iceland-Greenland area (Chart X and fig. 3B). Many cyclones formed east of the mountains in Alberta, triggered by perturbations moving in from the Pacific, while some Pacific storms actually moved across the mountains. Several of these storms were deep as they moved through western Canada with central pressures often below 1000 mb. Monthly mean sea level pressures averaged 7 mb. below normal over northern Alberta and also significantly below normal along the storm track from the Aleutians to southeastern Canada and near the Iceland-Greenland region (Chart XI inset). Hence a clear channel of low pressure along the line of this major storm track was in evidence on the mean sea

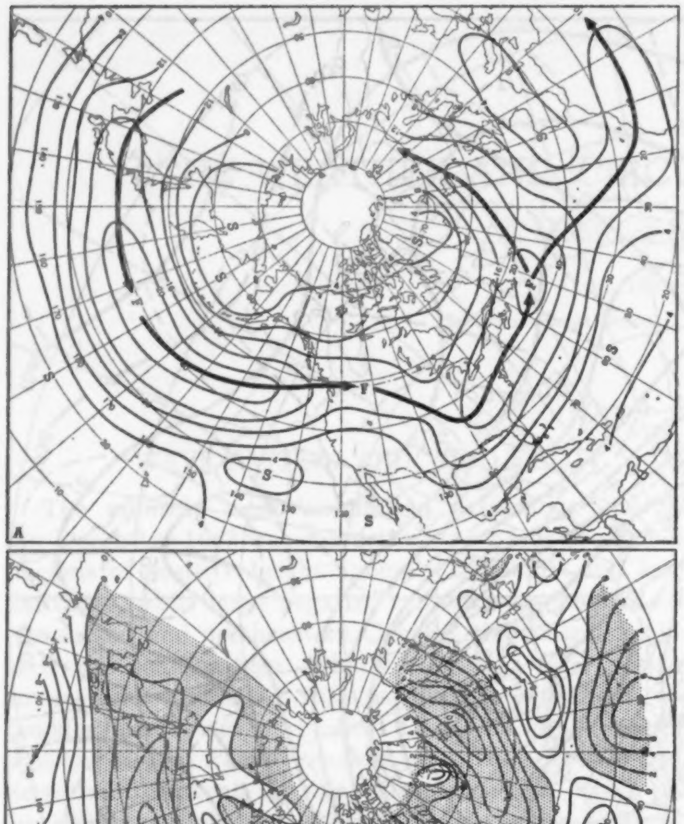

FIGURE 2.—Mean 700-mb. isotachs (A) and departure from normal wind speed (B) (both in meters per second) for November 29–December 28, 1953. Note broad bands of strong winds over oceanic areas and eastern United States. Wind speeds were predominantly in excess of normal north of about 35° N.

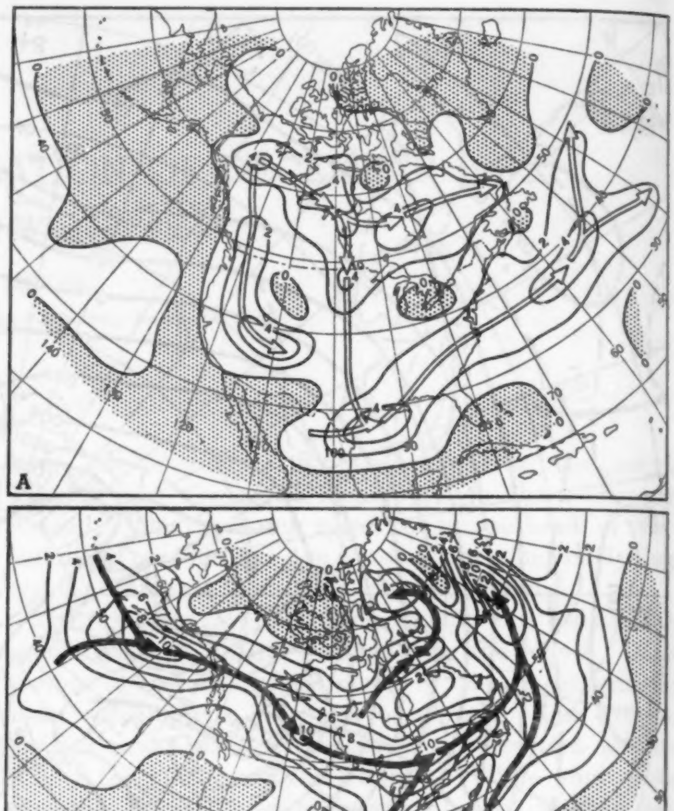

FIGURE 3.—Frequency of (A) anticyclone passages and (B) cyclone passages (within 5° squares at 45° N.) during December 1953. Well-defined anticyclone tracks are indicated by open arrows and cyclone tracks by solid arrows. Outstanding feature is the great concentration of cyclones traveling from the Gulf of Alaska eastward just north of Canadian-United States border and thence northeastward to the east side of Greenland. Of great importance to the precipitation regime over the United States were two parallel cyclone tracks originating over the Plateau and over the western Gulf of Mexico with a distinct minimum of cyclones in between, resulting in distinctly separate bands of heavy precipitation over eastern and central United States (Chart III-B).

level chart (Chart XI). The storm track paralleled the mean 700-mb. contours closely from northern British Columbia into the northern Atlantic (fig. 1) and remained in the cyclonic shear zone, poleward of the axis of maximum wind speed (fig. 2A). Closely related to the predominant storm track across Canada was a west-east zone of maximum frequency of surface frontal systems (fig. 4). As might be anticipated from the usual nature of fast-moving polar-front cyclones, this maximum concentration of fronts was generally located on the south side of the storm track. Along the Pacific Coast and in the eastern Pacific the displacement between the storm track and the region of maximum frontal frequency was quite large. This was related to the fact that many of the cyclones entering the Gulf of Alaska were of the old occluded type in which fronts no longer existed near the centers. In typical fashion frontal systems southeast of these Lows remained strong as they approached the Pacific Northwest steered by the main belt of fast westerlies.

Figure 3B shows that a few Alberta Lows traversed portions of the central northern border States. Aside from these there were several other cyclones affecting the United States during the month. These systems generally traveled along two distinct tracks as indicated in figure 3B. One of these, which was active primarily in the first decade of the month, was the path from the Southern Plateau northeastward across the Central Plains joining with the Alberta Low track northeast of the Great Lakes. The other extended from the Gulf of Mexico northeastward into the Atlantic off Cape Haterras. Both of these tracks are fairly typical during December and the number of storms traversing each of these tracks was probably not abnormal. The east coast track was essentially

parallel to the mean 700-mb. contours in that area and also to the trough extending from eastern Canada southwestward to Lower California (fig. 1). The central United States track was also parallel to the trough, but to the rear of it, so that it crossed the mean contours at a comparatively large angle. Meanwhile in the region located within about 10° to 15° of longitude east of the trough (i. e., from Texas northeastward to the Middle Atlantic States) there was virtually a complete absence of cyclones as well as a distinct minimum of fronts (fig. 4). The area just to the east of a well-defined deep mean trough would normally be expected to be the site of frequent storminess and considerable frontal activity. However, the trough over the central United States this month was not especially deep (a maximum of 80 feet below normal over Missouri) and also not too well defined since it was part of a broad cyclonic flow extending from the Rockies to the Atlantic. Thus, cyclonic activity over the States during December probably developed in response to the effects on a broad westerly current of fixed geographic features like the Rocky Mountains and the land-sea boundary along the Gulf and Atlantic coasts.

The precipitation regime over the United States during December was closely related to the aforementioned storm tracks, fronts, and circulation (Chart III-B). Precipitation generally exceeded normal amounts in areas along and north of the two storm tracks over the eastern and central United States; subnormal amounts prevailed along and north of the region of minimum storminess and frontal activity extending from Texas to the Middle Atlantic States. The lack of precipitation on the southeast side of Lows moving northeastward across the Plains States has often been noted. For example, a similar split in heavy precipitation areas associated with two separate storm tracks across the country was recently noted by Klein [2]. Above-normal precipitation occurring along the Canadian border from Montana to Minnesota was associated with some of the Alberta Lows which moved eastward very close to the border. The other region of above-normal precipitation, in Oregon and western Washington, was attributable to the fast westerlies striking the coast in this region (fig. 2) and the accompanying large number of frontal passages (fig. 4). Throughout the remainder of the West prevailing anticyclonic northerly flow (fig. 1) resulted in few fronts (fig. 4) and precipitation amounts which were generally subnormal.

TEMPERATURES RELATED TO ANTICYCLONE TRACKS AND CIRCULATION

Temperatures over the United States during December 1953 were greatly influenced by the dominant fast westerly flow prevailing over the Pacific and North America. As shown in Chart I-B the northern half of the country was considerably warmer than normal while the southern half averaged somewhat cooler than normal. In view of the fast westerly flow, the below-normal character of 700-mb. heights and sea level pressures in western and central

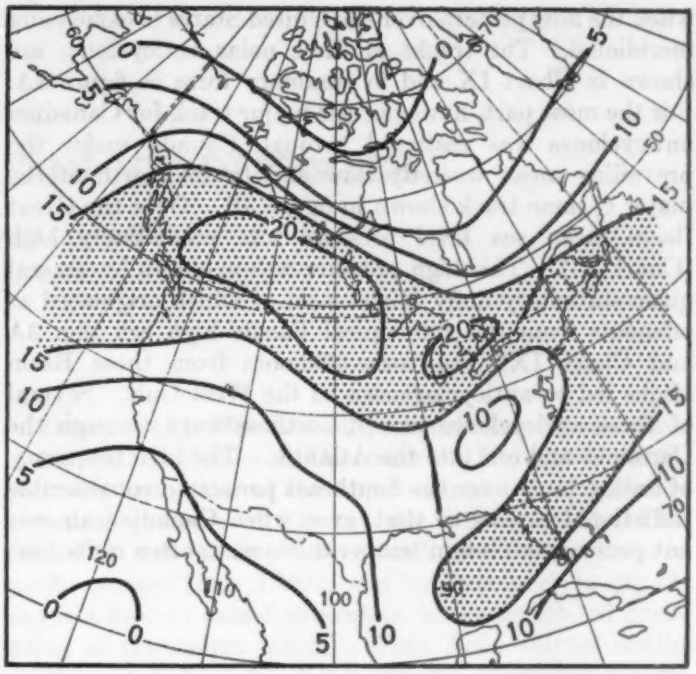

FIGURE 4.—Number of days with surface fronts (of any type) located within squares approximately 430 nautical miles on a side during the month of December 1953. Areas where fronts were present on 15 or more days are shaded. Zones of maximum frequency were located to the south of major storm tracks along northern border and east coast of United States. (Data from *Daily Weather Map*, 1830 GMT chart.)

Canada, and the associated frequency of Alberta Lows moving along the Canadian border, it is obvious that the United States was dominated by air masses of Pacific origin during much of the month. When Canadian polar air did invade the country the westerlies set in rapidly along the northern border so that cold weather was short-lived. Thus the entire northern half of the country was prevailingly warm even though 700-mb. heights were below normal and flow was slightly more northerly than normal over the Northern Plains to the rear of the trough. It was warmest (relative to normal) in the Northeast where heights were considerably above normal and flow was more southerly than normal, and also over Montana and western North Dakota where foehn winds prevailed as Pacific air masses crossed the mountains.

Northerly and northeasterly wind components with respect to normal over the West between the eastern Pacific ridge and the southwestern portion of the United States trough (fig. 1) were largely responsible for cold air in the Southern Plateau and Southern Rockies. The mean 700-mb. contours transported Pacific air masses of middle latitude origin into regions where normally flow is weaker and comes from lower latitudes of the Pacific. These Pacific air masses had little opportunity to warm appreciably as they traversed the broad region of pronounced cyclonic flow associated with the trough so that the South and Southeast experienced below-normal temperatures.

The Southeast was also cooled by a few outbreaks of Canadian polar air which plunged southward on occasions

when the flow pattern over the United States became more meridional. The tracks of these polar anticyclones are shown in Chart IX and in summary form in figure 3A. For the most part, however, the major track for Canadian anticyclones was eastward through Canada under the prevailing mean westerly flow and to the north of the major cyclone track shown in figure 3B. Over the Great Basin mean sea level pressure was prevailingly high (Chart XI). This high pressure was made up by several quasi-stationary daily Highs most of which originated as offshoots from the subtropical Pacific high cell (fig. 3A and Chart IX). In turn offshoots from these Basin Highs led to anticyclogenesis in the West Gulf. Several of these anticyclones moved northeastward through the Carolinas and out into the Atlantic. The high frequency of anticyclones over the Southeast permitted considerable radiational cooling so that, even when Canadian air was not present, minimum temperatures were often quite low.

As fast westerly flow continued at middle latitudes during December cold air accumulated over northern sections of Canada, mainly in the region of northerly flow to the rear of the deep trough over eastern Canada (fig. 1). As the month came to a close cold air began to occupy most of Canada, representing a considerable change from the warm state which had prevailed in the region throughout October and November [1].

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THE POLAR OUTBREAK IN MID-DECEMBER

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INTRODUCTION

Cold air associated with a large Arctic anticyclone entered the United States on December 16, 1953, bringing well below normal temperatures to the North Central and Southeastern States. Very large scale cyclonic circulation covering most of the area from 30° to 60° N. and 50° to 90° W. and extending through all levels, coupled with large-amplitude ridging aloft westward, contributed to the deep southward penetration of the cold air. A few of the interesting aspects of this anticyclone, which for convenience we shall call "Echo", will be discussed and also compared with features of the potential cold outbreak at the end of the month.

SYNOPTIC FEATURES

Cooling of the surface layer of air by radiation of its heat to the underlying snow- and ice-covered Arctic surface, apparently contributed to the building of Echo by the process described by Wexler [1]. Echo first appeared on the surface December 11 with a 1016-mb. central pressure near 75° N., 120° W. From about the same latitude on December 12, Echo started its south-southeastward journey pausing at about 60° N. until its central pressure reached 1035 mb. on December 15 (fig. 1). From this latitude and 100° W., the cell moved southward, slowly curving more to the south-southeast, with an average speed of 25 knots. The highest pressure noted on 6-hourly charts was 1042 mb. on December 17 in southern Iowa. From a position in northwest Alabama on December 18, the track became more easterly, and on the 19th Echo moved out into the Atlantic still maintaining a central pressure of 1030 mb. The track is shown in figure 2 and also on Chart IX.

According to the classification suggested by James [2], Echo was not an intense anticyclone until it reached the latitude of Iowa; it remained so until it moved off the east coast 3 days later.

This December polar outbreak was spectacular not for record high pressures or low temperatures, but more for the ease with which it penetrated far southward. The surface and 500-mb. charts for this period show that the High followed the path of least resistance between a Low to the east and a ridge to the west. Figures 1 and 3 show the large scale circulation at the surface and at 500 mb. on December 15. The Low in Quebec, beginning as a wave in the Gulf of Mexico on December 13, had moved northeastward to the east of the Appalachians and deepened to a central pressure of 975 mb. by December 15. This main Low was reinforced by a weak Low that had moved southeastward from Alberta and by December 16 (fig. 2) had lost its own closed circulation in the peripheral circulation of the deeper storm. When Echo started southward, most of the area between 30°–60° N. and 50°–90° W. was under the influence of very large scale cyclonic circulation at all levels. The semi-permanent 500-mb. elongated Low just off the west coast of Greenland served as a focal point for the cyclonic circulation aloft. A trough extended essentially north-south from this Low to the eastern Gulf of Mexico. In middle latitudes this trough had proceeded eastward at about 40 knots.

Simultaneously most of the United States had been influenced by the Great Basin High and by an mP High which had migrated east-southeastward to the western Gulf of Mexico by December 15. By 1830 GMT December 16, when Echo had passed into Minnesota, most of the western United States and Canada was covered with high pressure. The surface ridge line extended north-northwest–south-southeast from the Yucatan Peninsula through central United States to northwestern Canada (fig. 4). Aloft most of western United States and Canada showed the anticyclonic circulation and increasing amplitude of the 500-mb. ridge which extended north-south near the 120th meridian.

Another large scale feature (fig. 1 and 3) was the deep Low in the Gulf of Alaska. It reached a depth of 961 mb. at 1230 GMT December 14. At 500 mb. this circulation was centered near 50° N., 160° W.

VERTICAL STRUCTURE

Wexler [3] points out that in North America the polar anticyclone is characterized by a troposphere colder than its environment, especially in the lower portion, and a low (5 to 8 km.) warm (−50° C. to −65° C.) tropopause and warm lower stratosphere, while the warm anticyclone may have a thin cold layer at the surface, a warm troposphere, a high (12 to 17 km.) cold (−65° C. to −80° C.) tropopause and a cold lower stratosphere. As Echo started its southward plunge from a point west of Church-

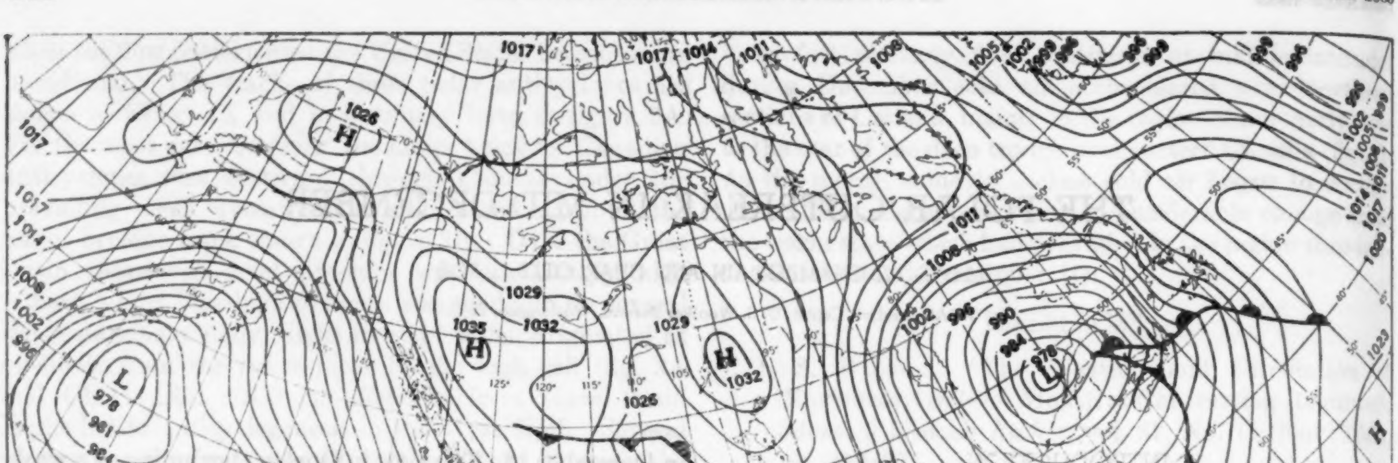

FIGURE 1.—Surface chart for 1230 GMT, December 15, 1953 showing position of Echo before it plunged southward. Note large-scale cyclonic circulation centered in southern Quebec.

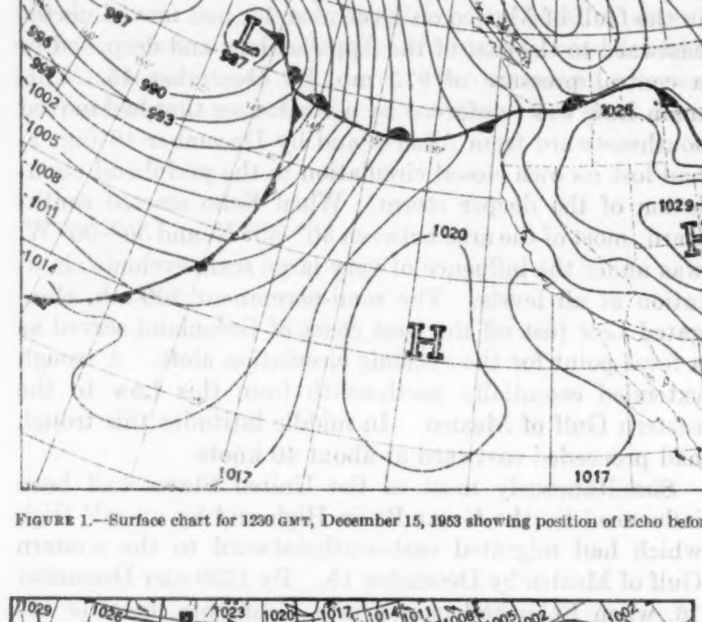

FIGURE 2.—Surface chart for 0030 GMT, December 16, 1953 showing complete track of Echo. 24-hour positions of center from 1230 GMT December 13 to 1230 GMT December 20 inclusive are marked by an "X". Shading shows areas of active precipitation.

ill, Manitoba, its characteristics met the cold High requirements shown by Wexler. Churchill's sounding at 0300 GMT, December 15 (fig. 5A) shows a shallow cold surface layer, and a warm (−49° C.), low (7.2 km.) tropopause. By 0300 GMT, December 16 when the center of cold air had moved to the south, Churchill showed a colder (−55° C.) and higher (8.5 km.) tropopause. However, at International Falls, Minn., throughout the period, the lowest tropopause recorded was 330 mb. (8.5 km.) (fig. 5B). At that time the polar characteristics showed slight modification and when the High center approached Nashville, Tenn. (fig. 6), the lowest tropopause shown was 240 mb. (above 10 km.). The Nashville sounding at 0300 GMT, December 19 (fig. 5C) showed 10° to 15° C. of warming throughout most of the troposphere during the 24-hour period while Nashville was located within the central isobar of Echo.

TEMPERATURE FIELD

The 1000- to 500-mb. thickness chart for 1500 GMT, December 15 (fig. 7) shows an extensive area of cold advection east of 115° W. and from Canada to the Gulf of Mexico. This is one example that illustrates how cold air could be extrapolated with the 500-mb. flow as an aid to forecasting the cold outbreak penetrating the southern

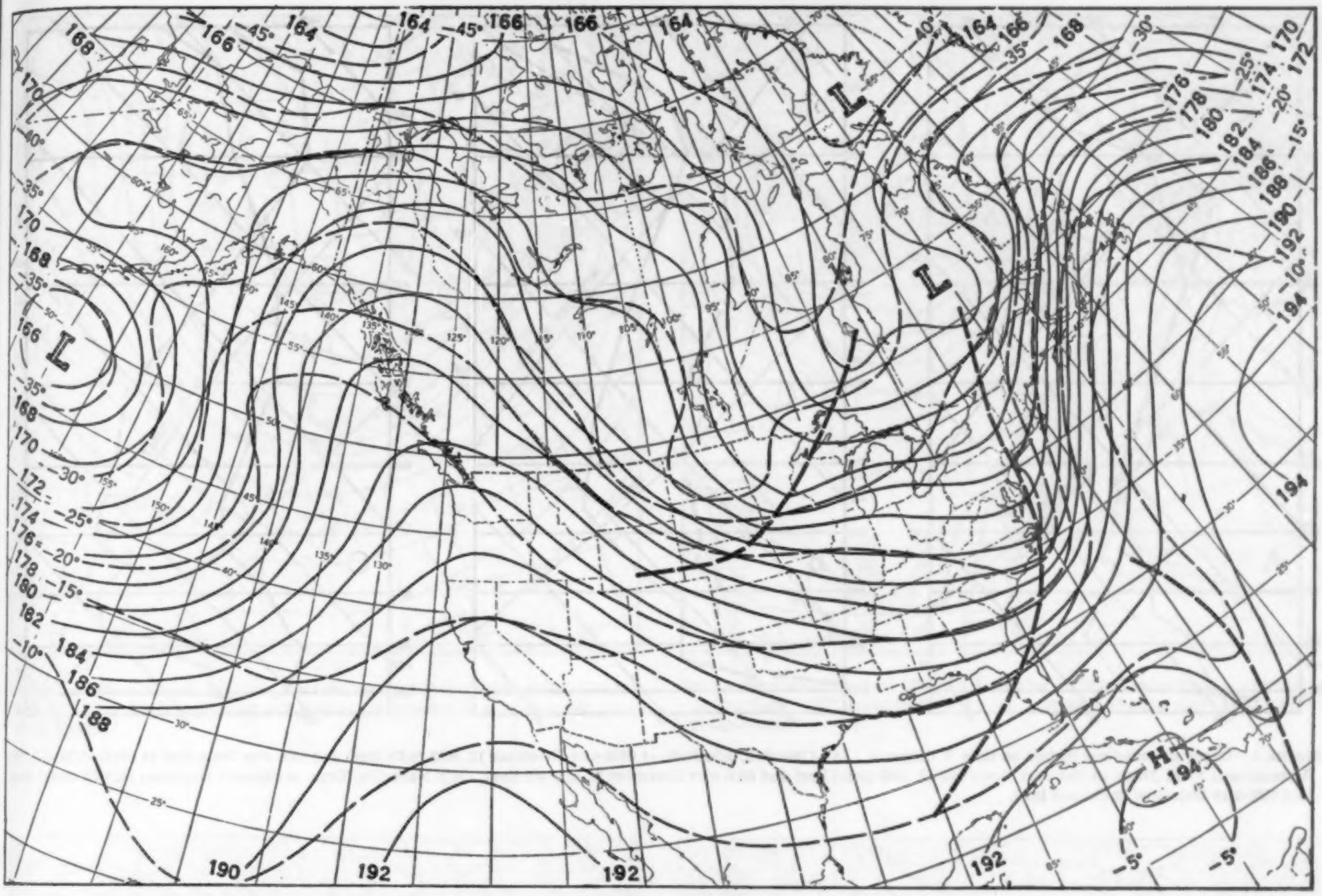

FIGURE 3.—500-mb. chart for 1500 GMT, December 15, 1953. Height contours (solid lines) are labeled in hundreds of geopotential feet, isotherms (dashed lines) in °C. Heavy dashed lines indicate troughs. Note ridge over Alaska and northwestern Canada and northwest flow from western Canada to the southeastern United States.

States (fig. 8). A comparison with a potential polar outbreak on December 28 using the above point will be made later.

In connection with this cold outbreak, the 1000- to 500-mb. thickness departure from normal is of interest. Figure 9 shows above and below normal thickness areas for 1500 GMT, December 18, and the advancing positions of the minus 400-ft. thickness departure contour from 1500 GMT December 15 to 1500 GMT, December 18. The departure gradient points out a region of strong temperature contrast from 95° W. to 75° W. and from the Gulf of Mexico to Canada. As a 400-ft. thickness departure from normal is equivalent to an 11° F. departure from normal of the mean virtual temperature for the 1000- to 500-mb. layer, the data in figure 9 may be compared with observed temperature departures. Table 1, listing surface minimum temperatures and departures from normal, shows that surface drops in some places far exceeded the mean virtual temperature drop for the 1000- to 500-mb. layer. Although only one record was broken (Lexington, Ky.), the departure from normal ranged from −12° to −25° F. Note that the highest pressure and minimum temperature for the month for most of these stations occurred on approximately the same day.

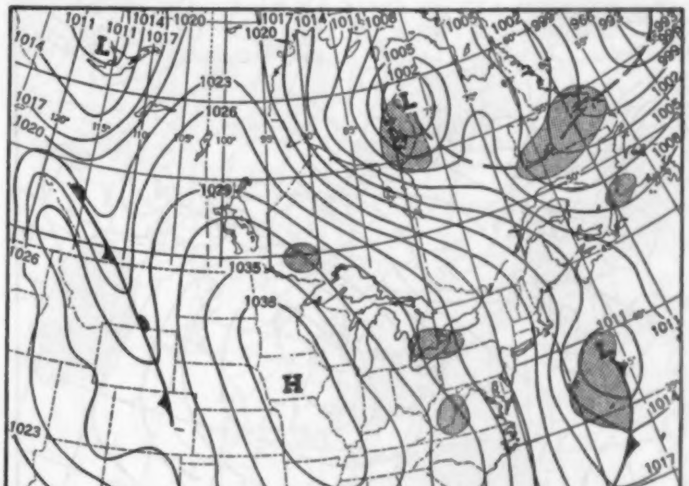

FIGURE 4.—Surface chart for 1230 GMT, December 17, 1953 showing most of the United States under the influence of Echo. Shading shows areas of active precipitation.

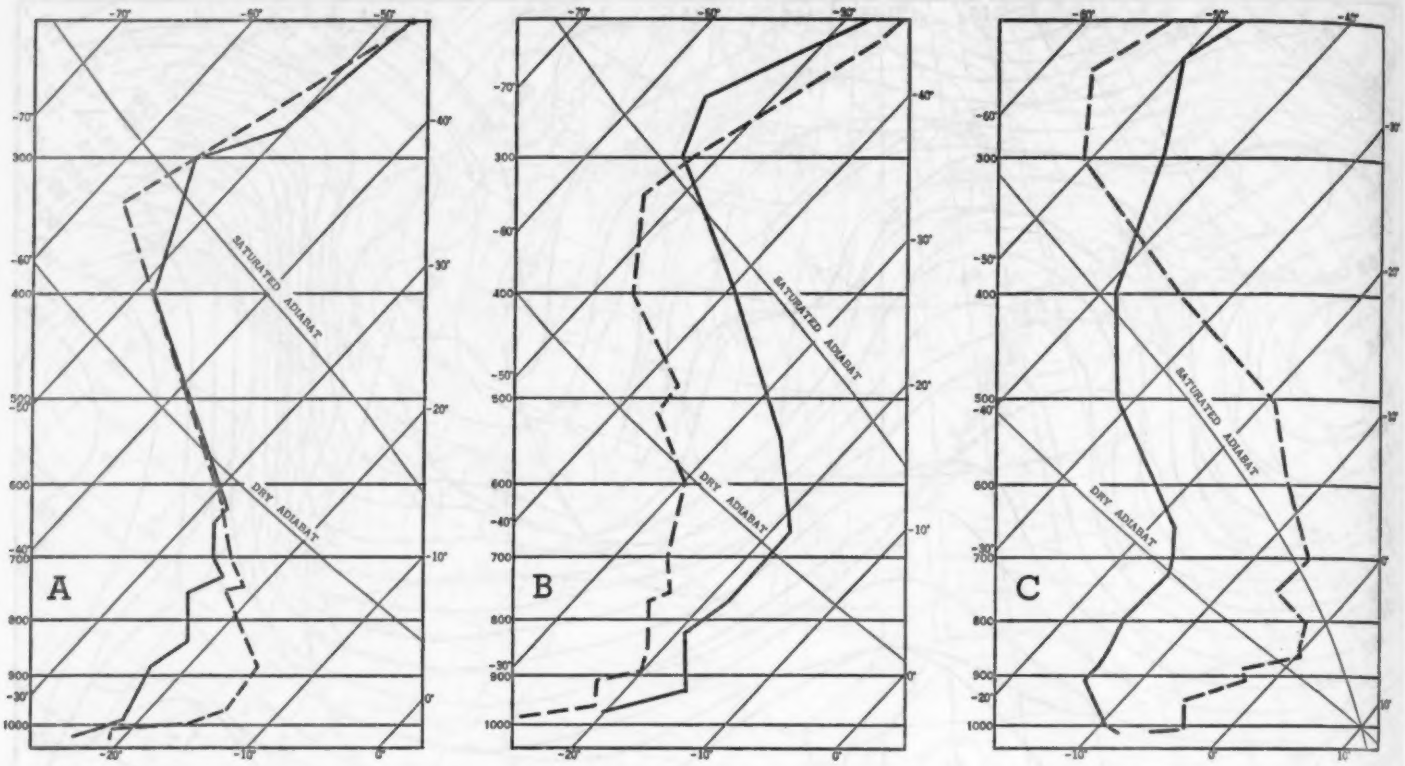

FIGURE 5.—Upper air soundings plotted on skew T diagrams. (A) Churchill, Manitoba at 0300 GMT December 15, 1953 (solid line) and 0300 GMT December 16 (dashed line). (B) International Falls, Minn. at 0300 GMT December 15, 1953 (solid line) and 0300 GMT December 16 (dashed line). (C) Nashville, Tenn. at 0300 GMT December 18, 1953 (solid line) and 0300 GMT December 19 (dashed line).

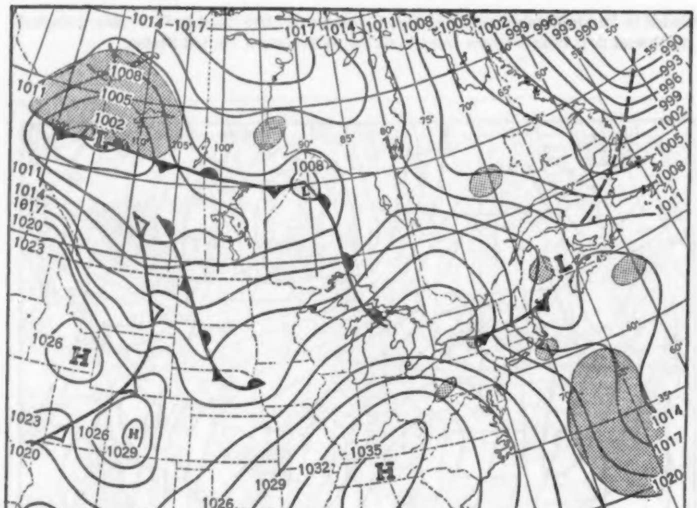

FIGURE 6.—Surface chart for 0030 GMT December 19, 1953. Shading shows areas of active precipitation.

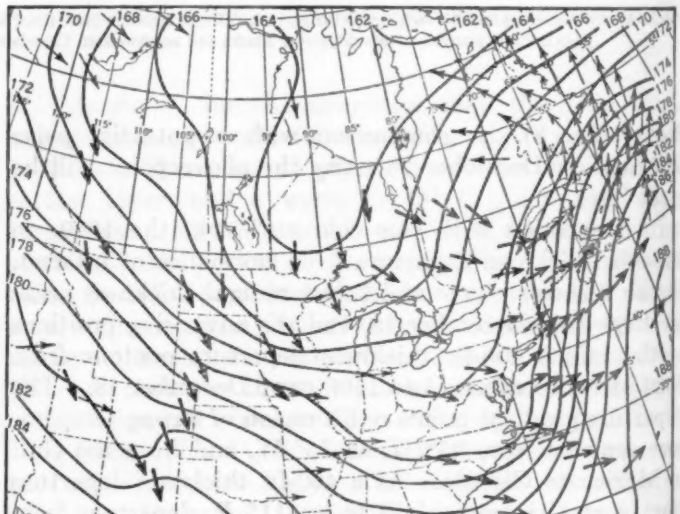

FIGURE 7.—1000- to 500-mb. thickness chart for 1500 GMT, December 15, 1953. Thickness, labeled in hundreds of feet, is proportional to mean virtual temperature. Advection arrows (thin shaft=warm advection, thick shaft=cold advection) are obtained from mean flow against 1000- to 500-mb. thickness lines.

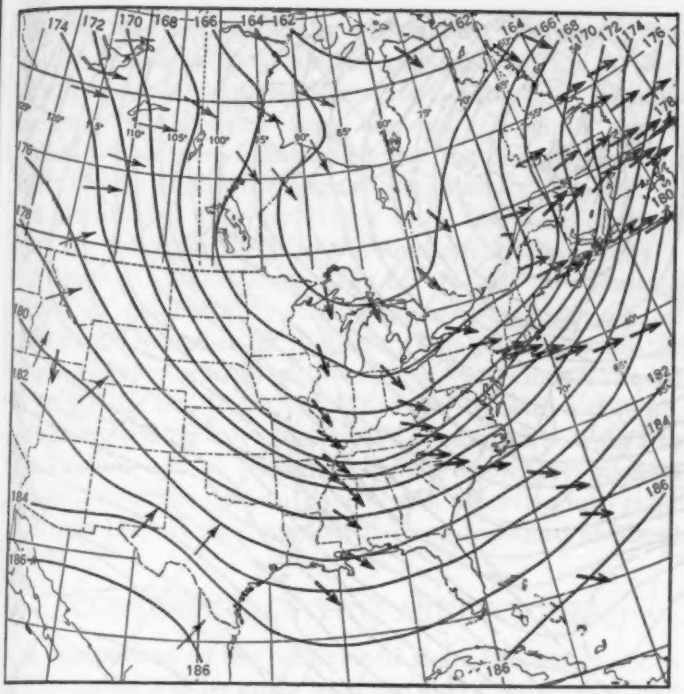

Figure 8.—1000- to 500-mb. thickness chart for 1500 GMT December 16, 1953. Compare with figure 7 and note southward and eastward progression of cold advection (thick shaft) arrows.

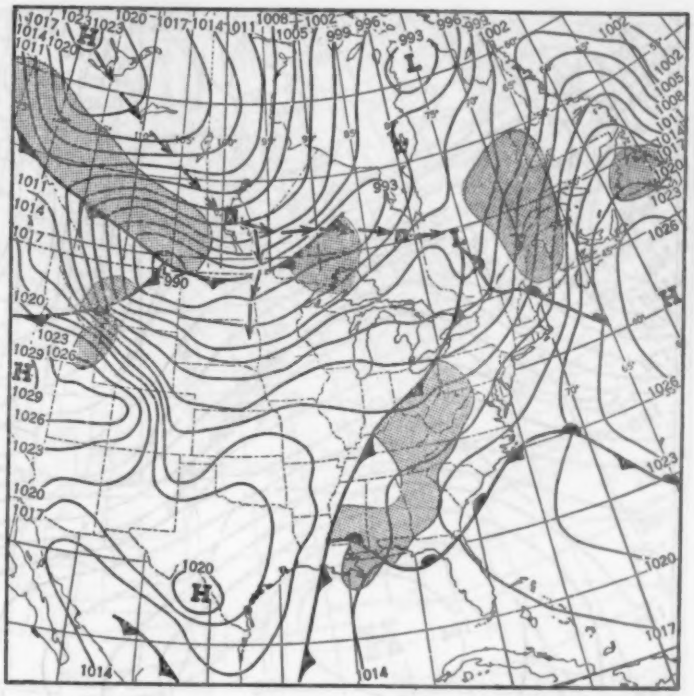

Figure 10.—Surface chart for 1830 GMT, December 28, 1953 showing track of Fox on succeeding days. "X" marks position at 24-hr. intervals. Shading shows areas of active precipitation.

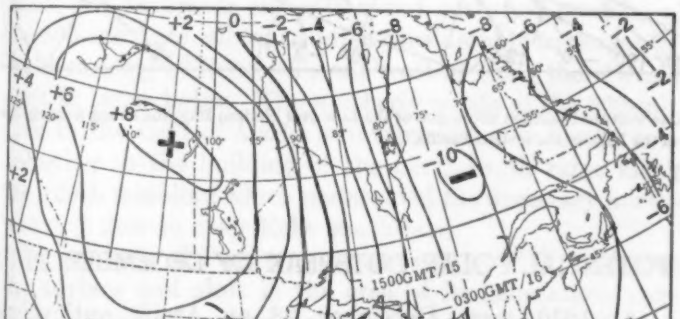

Figure 9.—Departure from normal 1000- to 500-mb. thickness chart (labeled in hundreds of feet) for 1500 GMT, December 15, 1953. "X" marks surface position of Echo at this time. Heavy dashed lines give position of minus 400-ft. departure from normal contour at 12-hr. intervals from 1500 GMT, December 15 to 0300 GMT December 18 inclusive showing its southward progression.

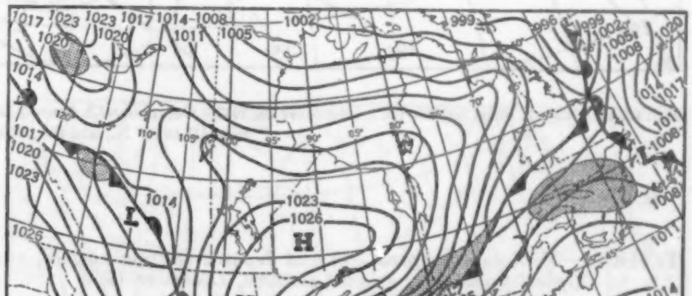

Figure 11.—Surface chart for 0030 GMT, December 30 when Fox showed signs of splitting into two cells. Shading shows areas of active precipitation.

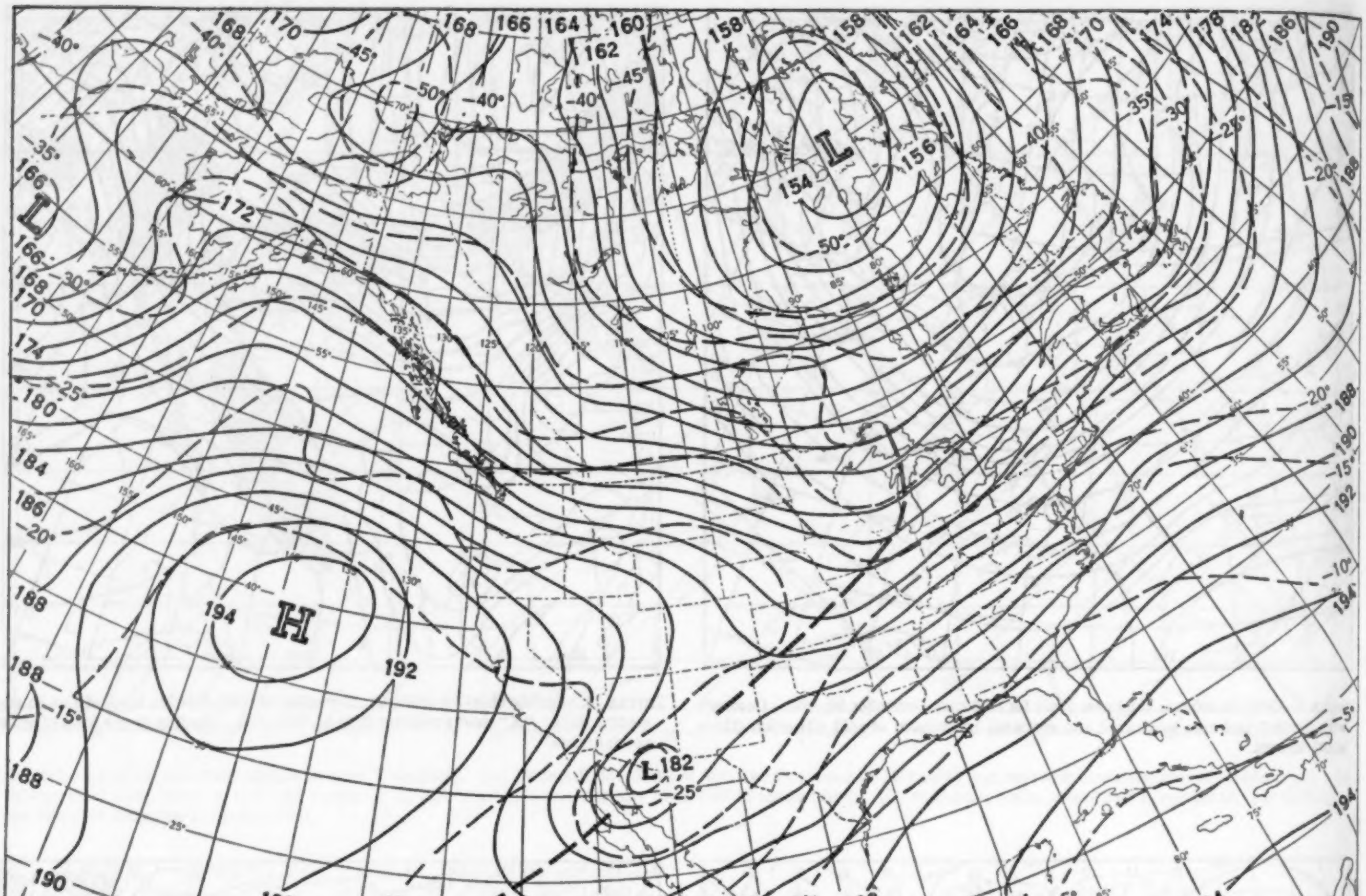

FIGURE 12.—500-mb. chart for 1500 GMT, December 28, 1953. Compare with figure 3 and note westward position and depth of the Low over Hudson Bay, the strong westerly flow from 45° to 60° N., and the position of the High in the eastern Pacific.

TABLE 1.—*Minimum temperatures and departures from normal, and highest pressure at selected stations, December 1953*

Station	Surface temperature			Sea level pressure		Remarks
	Date	Min. for month (° F.)	Departure from normal (° F.)	Date	Highest for month (mb.)	
Birmingham, Ala	18	14	−21	18	1039.3	
Mobile, Ala	18, 19	27	−19, −13	18	1037.6	
Jacksonville, Fla	18	26	−19	18	1034.9	
Miami, Fla	18, 19	45	−14, −12	------	------	City office.
Tampa, Fla	18	36	−18	18	1033.5	
Atlanta, Ga	18	13	−21	18	1037.6	
Savannah, Ga	19	17	−19	18	1035.6	
Chicago, Ill	18	0	−14	17	1033.9	
Lexington, Ky	17, 18	0	−25, −22	18	1038.3	Record low temp. for these dates.
Baltimore, Md	18	15	−14	24	1032.2	
Jackson, Miss	19	22	−12	18	1039.3	Not lowest min. for month.
Charlotte, N. C	18	11	−20	18	1035.2	
Hatteras, N. C	18	27	−18	19	1032.9	
Dayton, Ohio	18	−3	−23	18	1035.6	Min. temp. coldest since Dec. 16, 1951, when −15 recorded.
Philadelphia, Pa	18	14	−13	24	1030.5	
Columbia, S. C	18	12	−22	18	1036.2	Columbia Airport.
Charleston, S. C	19	16	−18	19	1035.2	Municipal airport.
Nashville, Tenn	18	9	−21	18	1039.6	
Elkins, W. Va	19	0	−14	24	1034.5	
Washington, D. C	18	17	−14	24	1032.8	National Airport

POTENTIAL POLAR OUTBREAK OF DECEMBER 28–31

At 1830 GMT, December 28 an Arctic anticyclone appeared as a 1024-mb. cell centered about 65° N., 125° W. oriented northwest-southeast (fig. 10). This anticyclone, which will be referred to as "Fox", moved southeastward at about 45 knots. By 1830 GMT December 29, Fox, with a central pressure of 1029 mb. was centered about 100 miles north of the western Minnesota-Canadian border. Six hours later (fig. 11) surface data indicated the beginning of the splitting of Fox with one center moving southward and one eastward. The southward portion of Fox was small and did not bring very cold temperatures south of Iowa. The eastbound portion was more intense and brought colder temperatures eastward along the Canadian border before curving more northeastward.

At 1830 GMT, December 28 (fig. 10), the main Low in the east (not shown) was near 70° N. and just west of Greenland with a secondary center about 60° N., 80° W. A weak, rapidly moving, 1001-mb. Low, centered in southern Quebec, had formed 60 hours earlier in Alberta.

Its track had been generally west to east dipping into the United States in the Dakotas and Minnesota. A third Low was centered along the eastern Montana-Canadian border. At the same time western and south central United States were influenced by an eastern wedge of the main Pacific High which was centered at 40° N., 135° W. and dominated the circulation from the west coast to 155° W. and from 15°N. to the southern Alaskan coast.

A deep, 15,300-ft. Low near 65° N., 80° W. was the center of extensive cyclonic circulation at 500 mb. at 1500 GMT, December 28 (fig. 12). This pattern indicated an area of strong west-northwest and west winds from 45° N. to 60° N. and from 120° W. to 60° W. with a 500-mb. trough extending from the Great Lakes southwestward to the Pacific. As at sea level, high pressure prevailed at 500-mb. over the eastern Pacific with a north-south ridge at about 145° W. and another pushing eastward at about 40° N.

COMPARISON OF TWO ANTICYCLONES

A comparison of the behavior of these two anticyclones of December will be made with the aid of the surface and 500-mb. charts and the 1000- to 500-mb. thickness charts showing areas of advection. As pointed out, in the case of Echo the entire synoptic picture favored southward penetration. The depth of the surface Low, the extensive area covered by the cyclonic circulation to the east of Echo, the favorable elongation and eastward position of the 500-mb. Low, all contributed considerably to the southward steering of Echo. To the west of Echo there was a shift to lower index. The southerly winds of the 500-mb. Low in the Gulf of Alaska sent warm air over Alaska contributing to the building of the north-south ridge along the 120th meridian which maintained the necessary northwesterly flow to steer Echo southward.

In the case of Fox, temperatures 10°–15° C. colder at the surface and aloft in the area of its generation, very large 3-hourly pressure tendencies at 1830 GMT, December 28 south and west of the high axis, and no apparent block to southeastward motion, were tempting factors favoring a forecast of a cold outbreak. In the overall picture, however, the stage was not set for far southward penetration of Fox. The absence of a deep surface Low in the northeast United States was conspicuous. Lows had been weak and rapidly moving near the United States-Canadian border. The much deeper (15,300-ft.) 500-mb. Low which was farther west, 65° N., 80° W. (compare figs. 3 and 12), set up much strong west to east flow in the latitude of Fox's formation. The strong northwest winds on the western side of the 500-mb. Low accounted for the 45-knot southeastward movement of Fox before it divided into two cells. In the west at this time a return to higher index and stronger westerly flow at higher latitudes accounted for a more easterly track of the main body of cold air associated with Fox. The Pacific 500-mb. Low was weak and too far west (fig. 12) to assist in building a ridge that would immediately move Fox southward. The

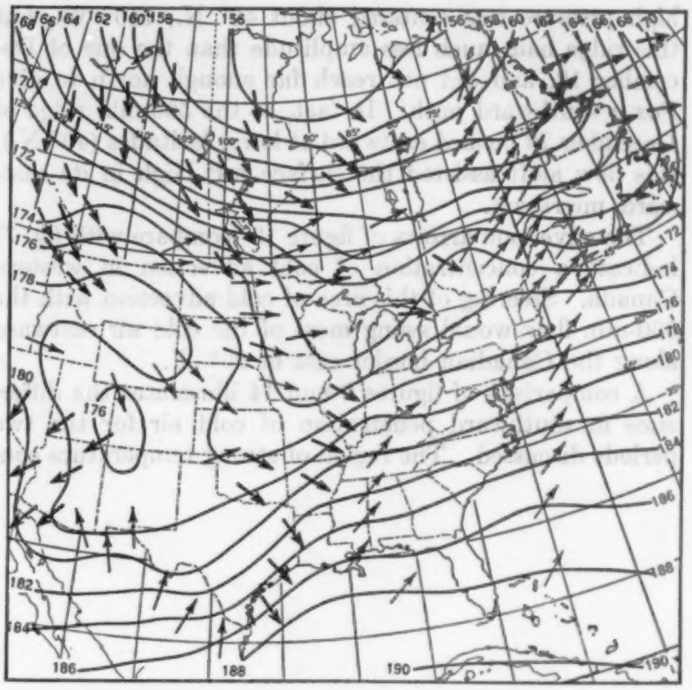

FIGURE 13.—1000- to 500-mb. thickness (labeled in hundreds of feet), 1500 GMT, December 28, 1953, with advection arrows (thin shaft=warm advection, thick shaft=cold advection). Compare with figure 7.

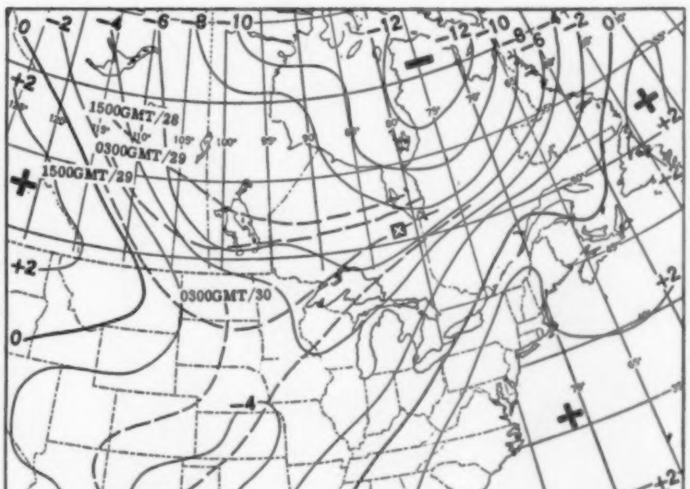

FIGURE 14.—Departure from normal 1000- to 500-mb. thickness (labeled in hundreds of feet) for 1500 GMT, December 30, 1953. "X" marks surface position of Fox at this time. Heavy dashed lines represent the 12-hr. positions of the minus 400-ft. departure from normal contour from 1500 GMT December 28 to 0300 GMT December 30 inclusive. Compare with figure 9 and note the marked difference in orientation of the negative departure area.

high pressure was centered about 40° N., 140° W., but this ridge had much less amplitude than the one of December 18, and did not reach far enough north to give Fox a southward push. In fact, as the 500-mb. ridge of December 28 pushed eastward at lower latitudes (40° N.), this flow aloft assisted the surface mP High in its eastward migration.

The advection arrows of figure 13 (compare with fig. 7) indicate a concentration of cold advection in western Canada. Steering of this area of cold advection with the 500-mb. flow would swing most of the cold air eastward along the Canadian border east of 90° W.

A comparison of figures 9 and 14 illustrates the difference in southward penetration of cold air for the two periods discussed. The region of strong temperature contrast in the case of Fox remained north of the United States (fig. 14) and the −400-ft. departure contour reached southward only on the 0300 GMT December 30 chart.

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2. R. W. James, "The Latitude Dependency in Cyclones and Anticyclones", *Journal of Meteorology*, vol. 9, No. 4, Aug. 1952, pp. 243–251.
3. H. Wexler, "Anticyclones", *Compendium of Meteorology*, American Meteorological Society, Boston, 1951, pp. 621–629.

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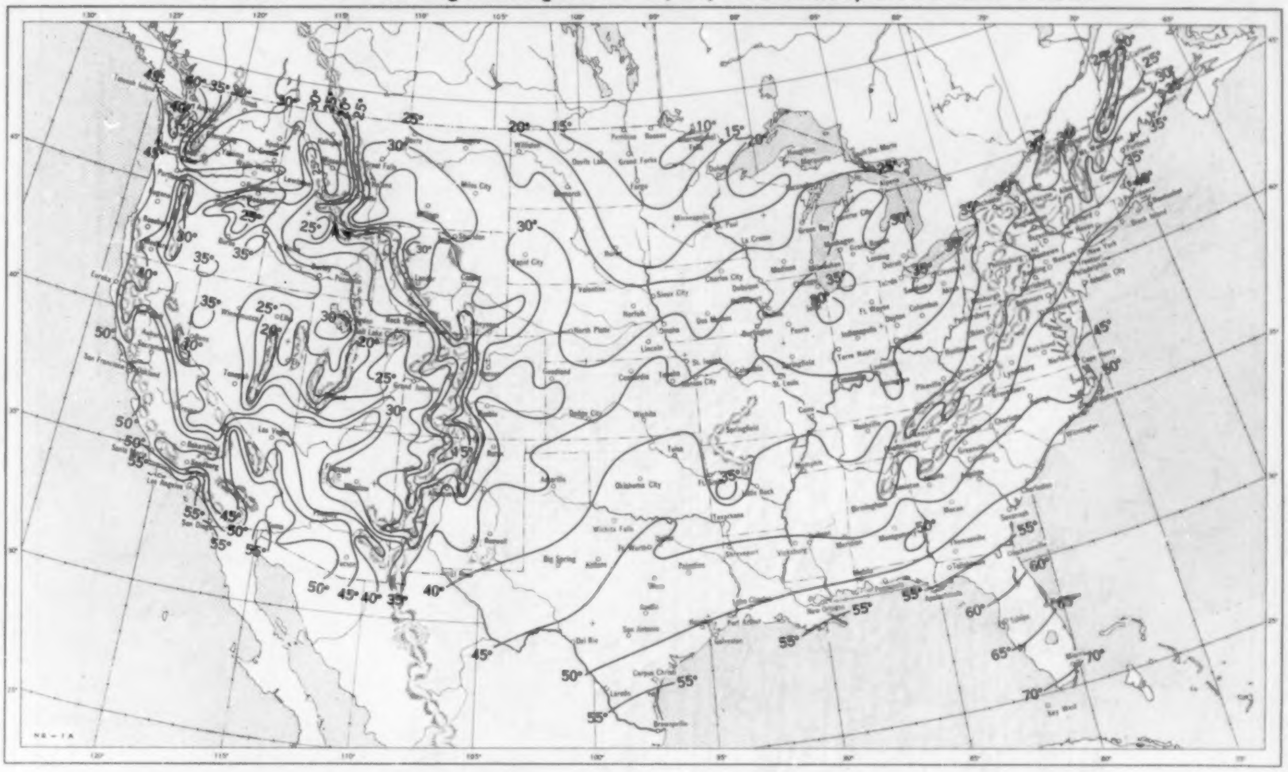
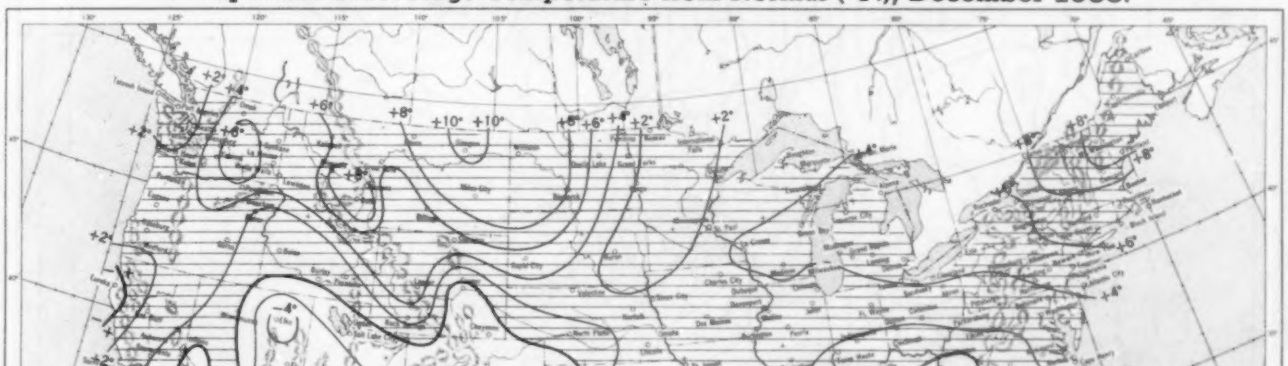
Chart I. A. Average Temperature (°F.) at Surface, December 1953.

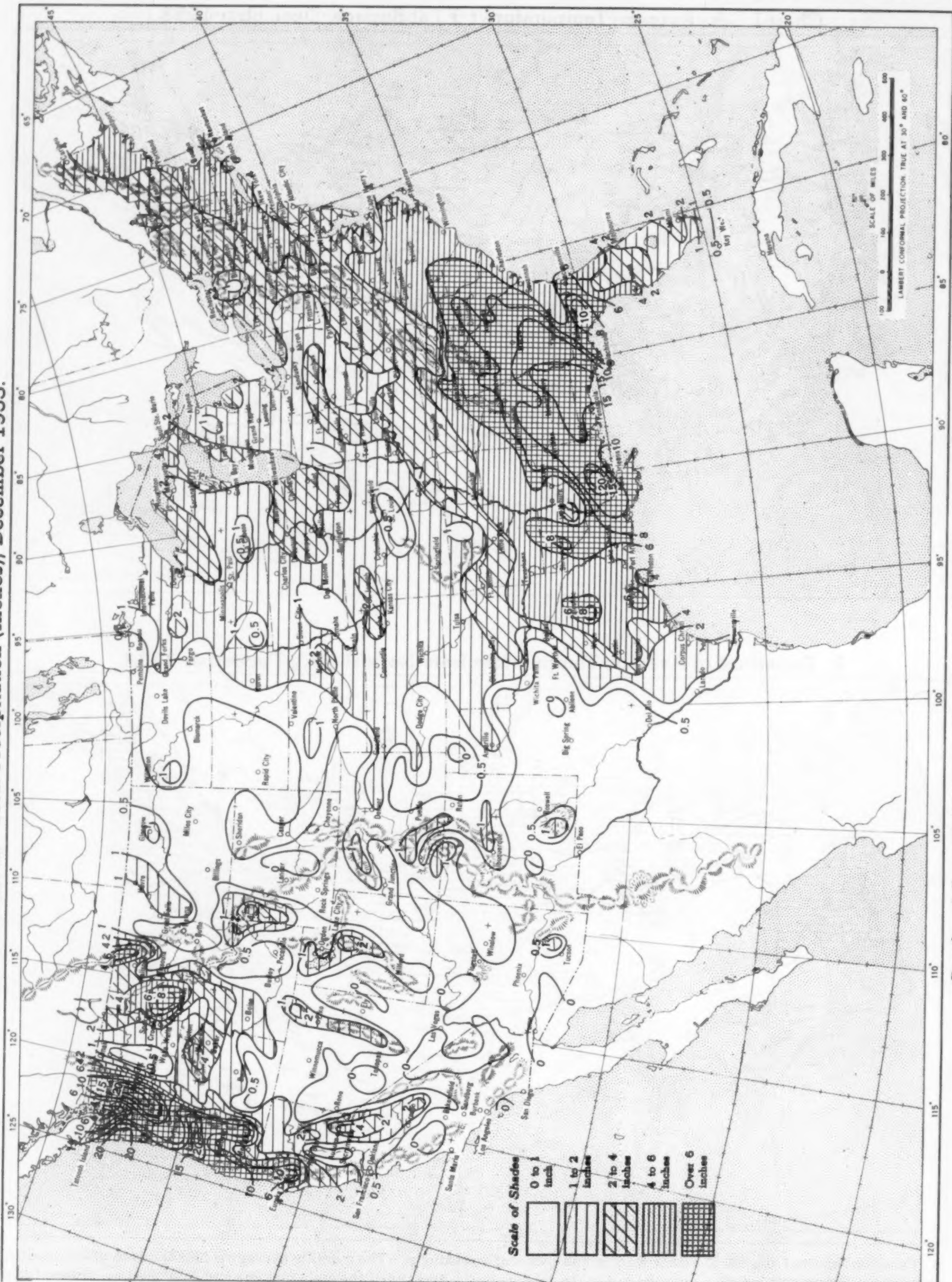


B. Departure of Average Temperature from Normal (°F.), December 1953.



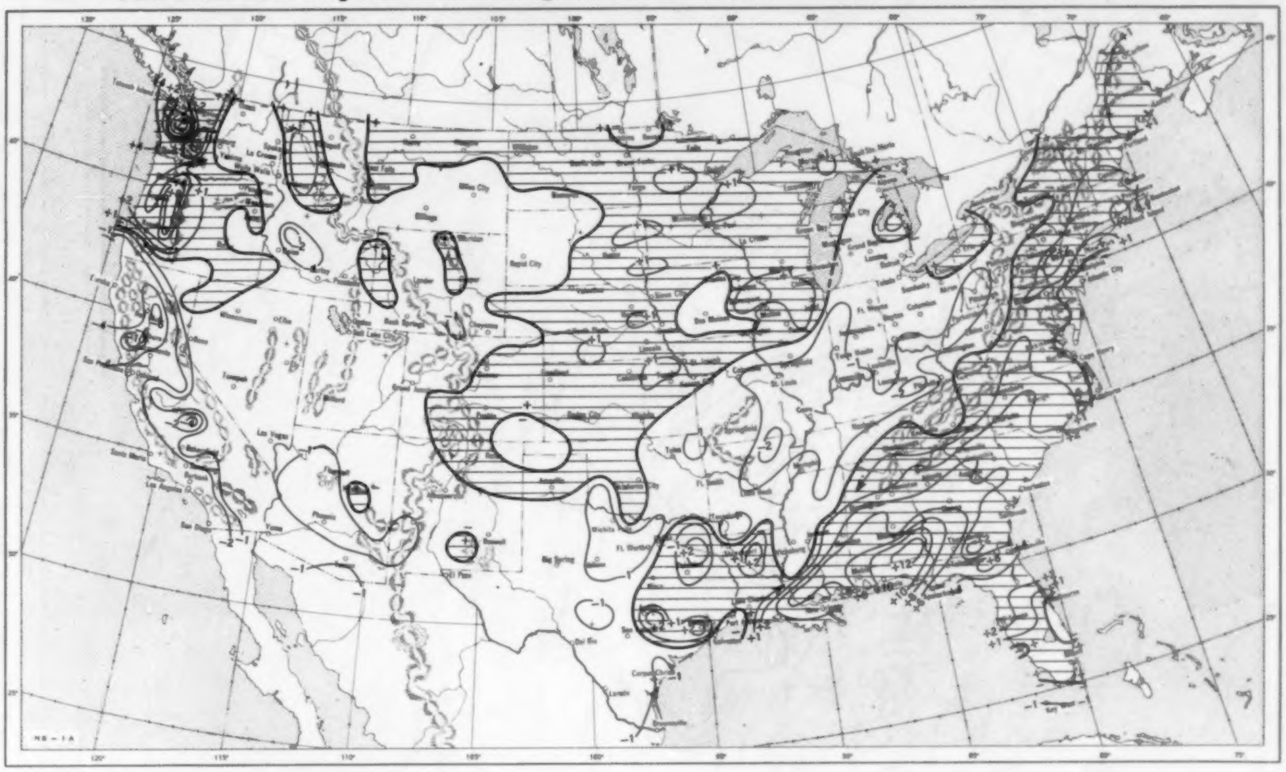
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), December 1953.

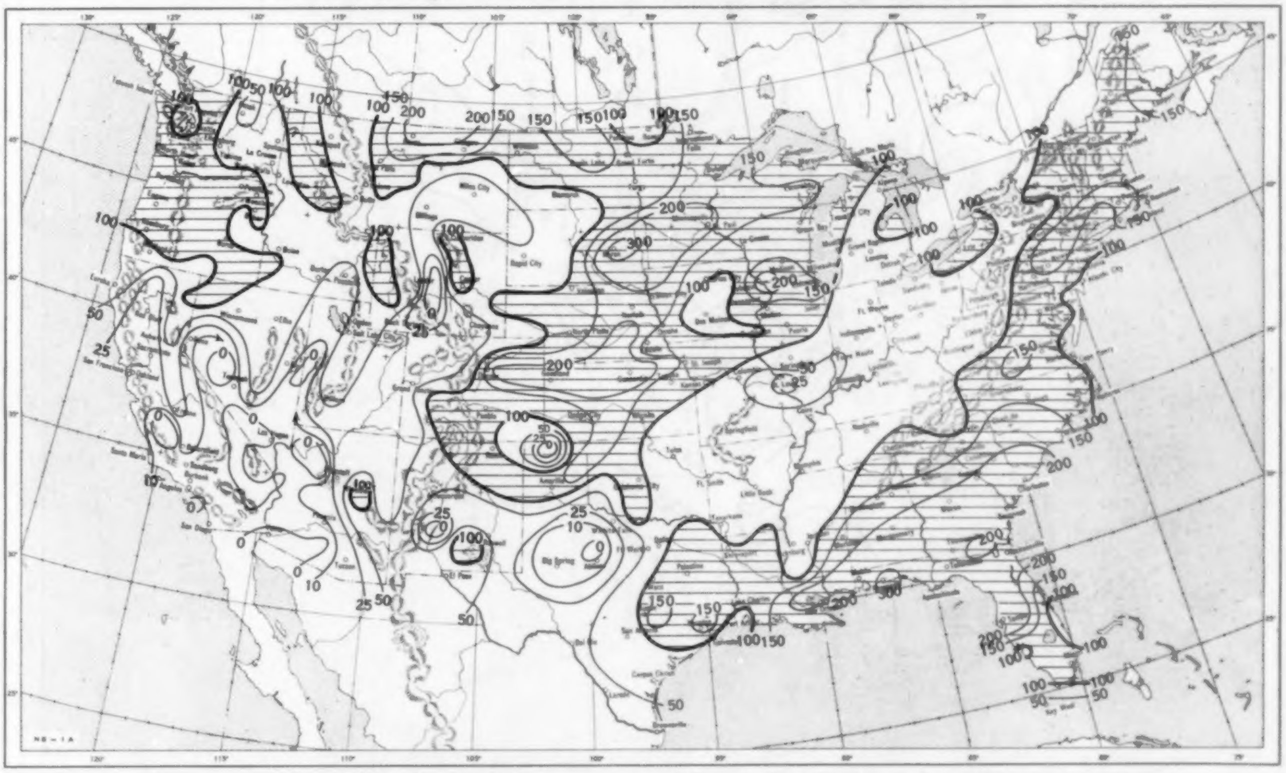


Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), December 1953.

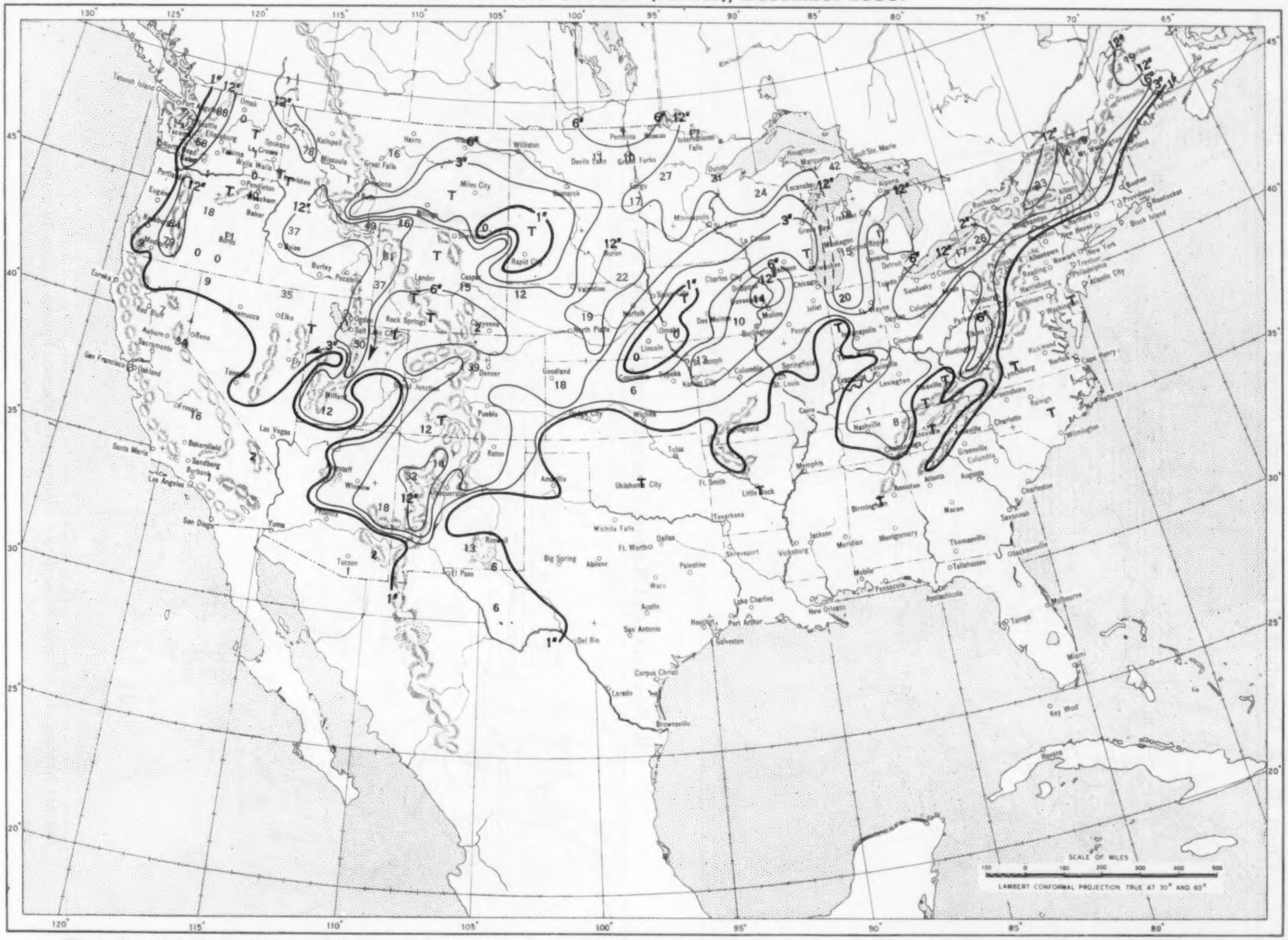


B. Percentage of Normal Precipitation, December 1953.



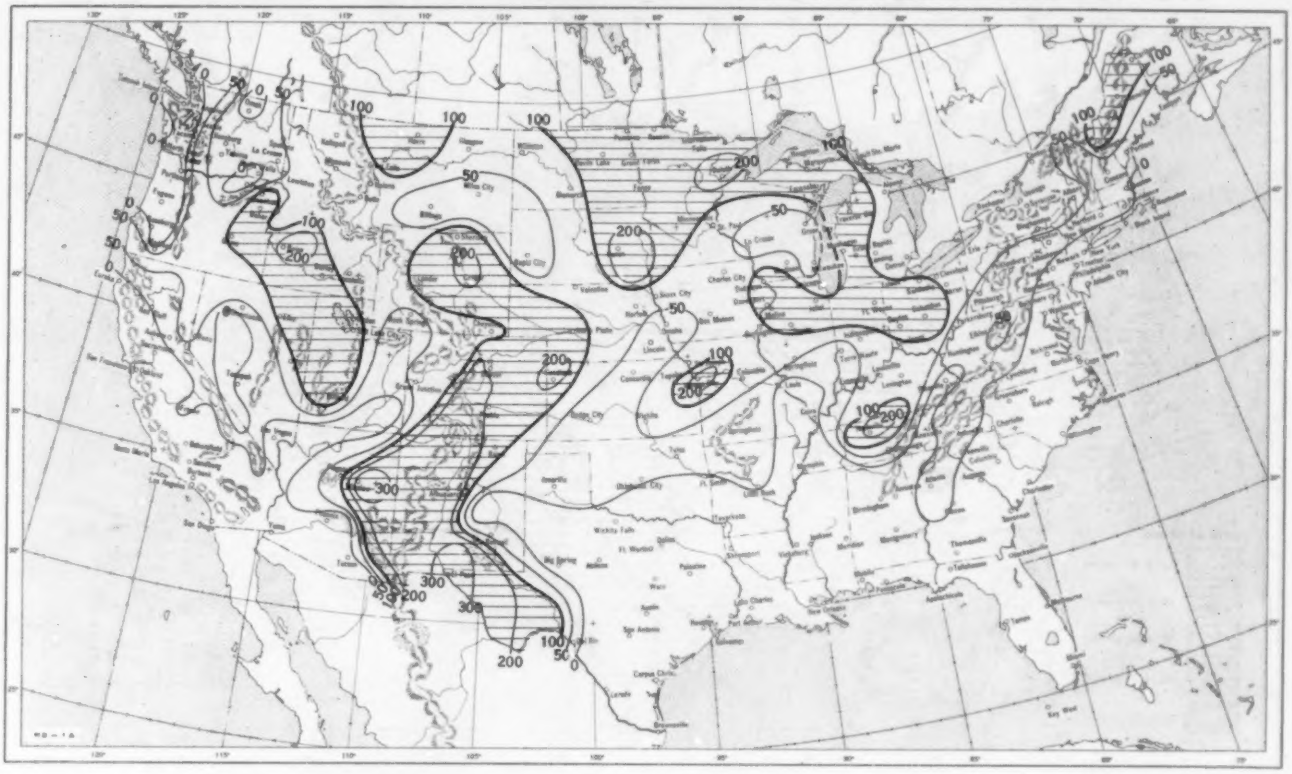
Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), December 1953.

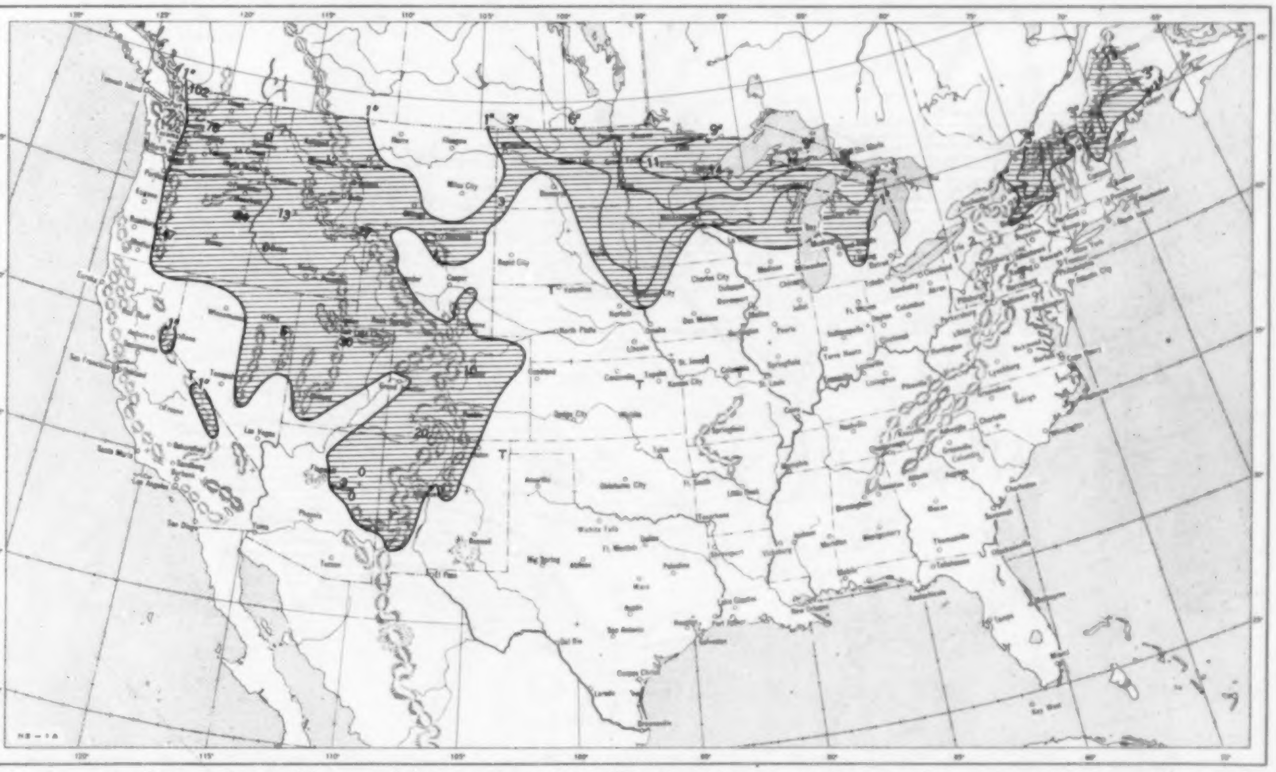


This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, December 1953.

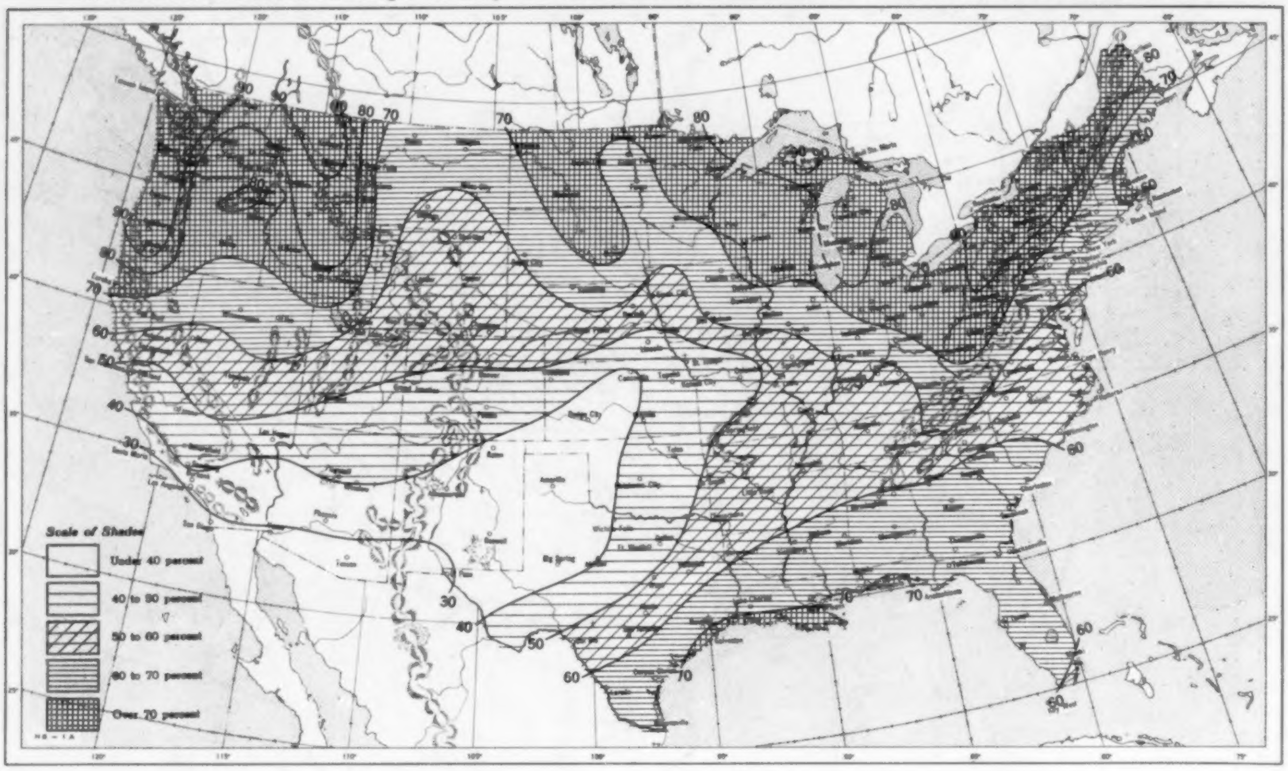


B. Depth of Snow on Ground (Inches), 7:30 a. m. E. S. T., December 29, 1953.



A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record.
B. Shows depth currently on ground at 7:30 a. m. E. S. T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

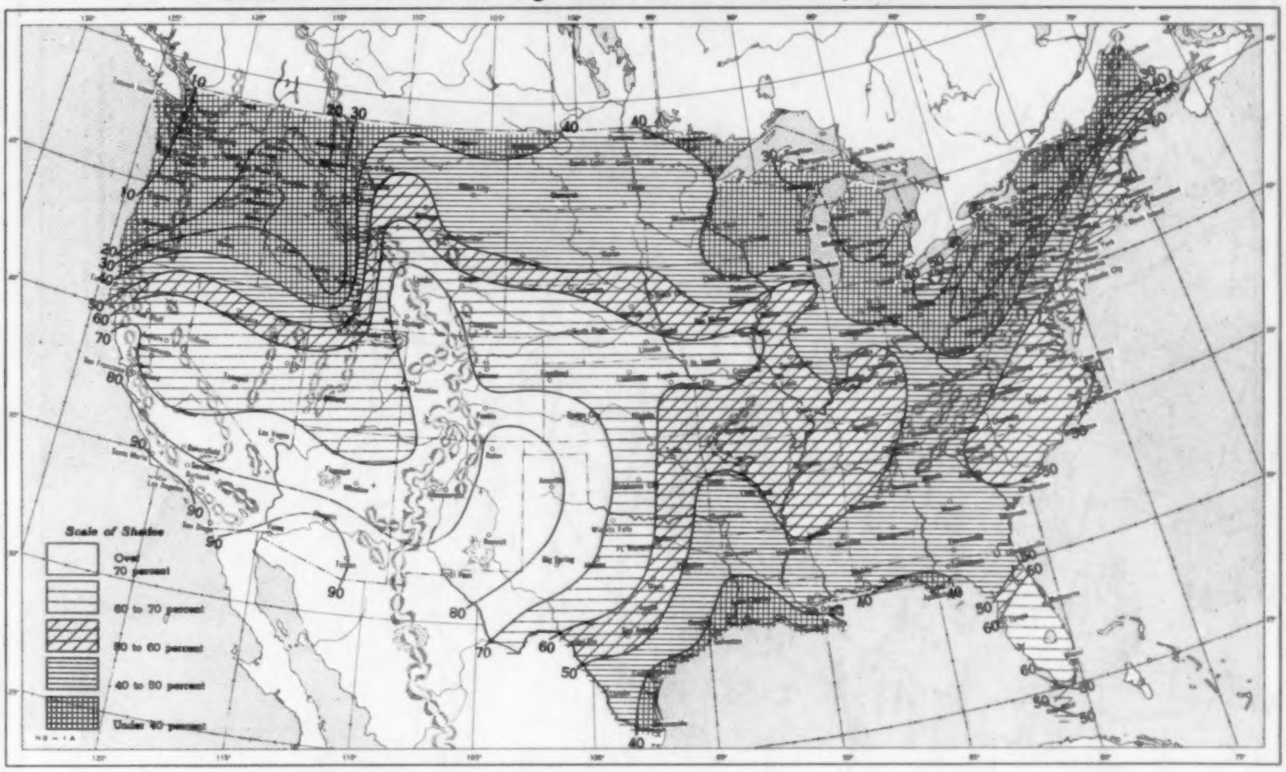
Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, December 1953.



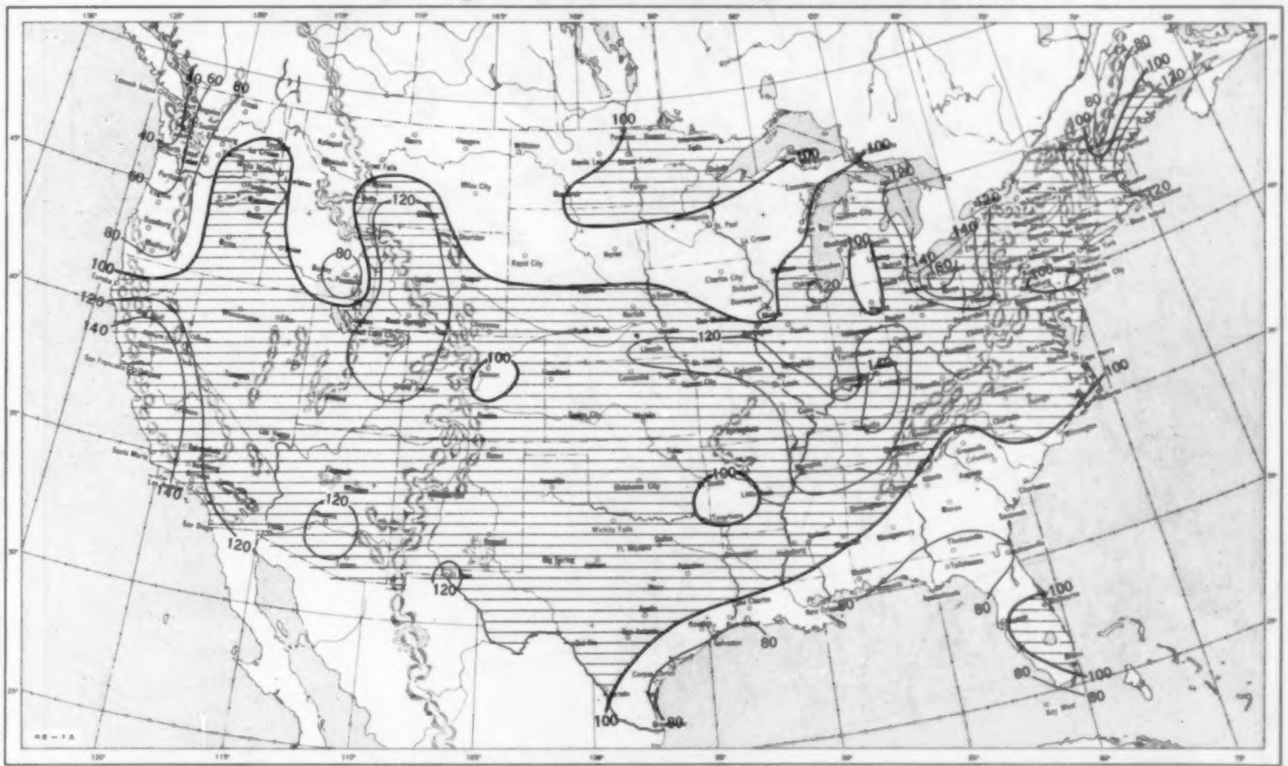
B. Percentage of Normal Sky Cover Between Sunrise and Sunset, December 1953.

A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, December 1953.



B. Percentage of Normal Sunshine, December 1953.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, December 1953. Inset: Percentage of Normal Average Daily Solar Radiation, December 1953.

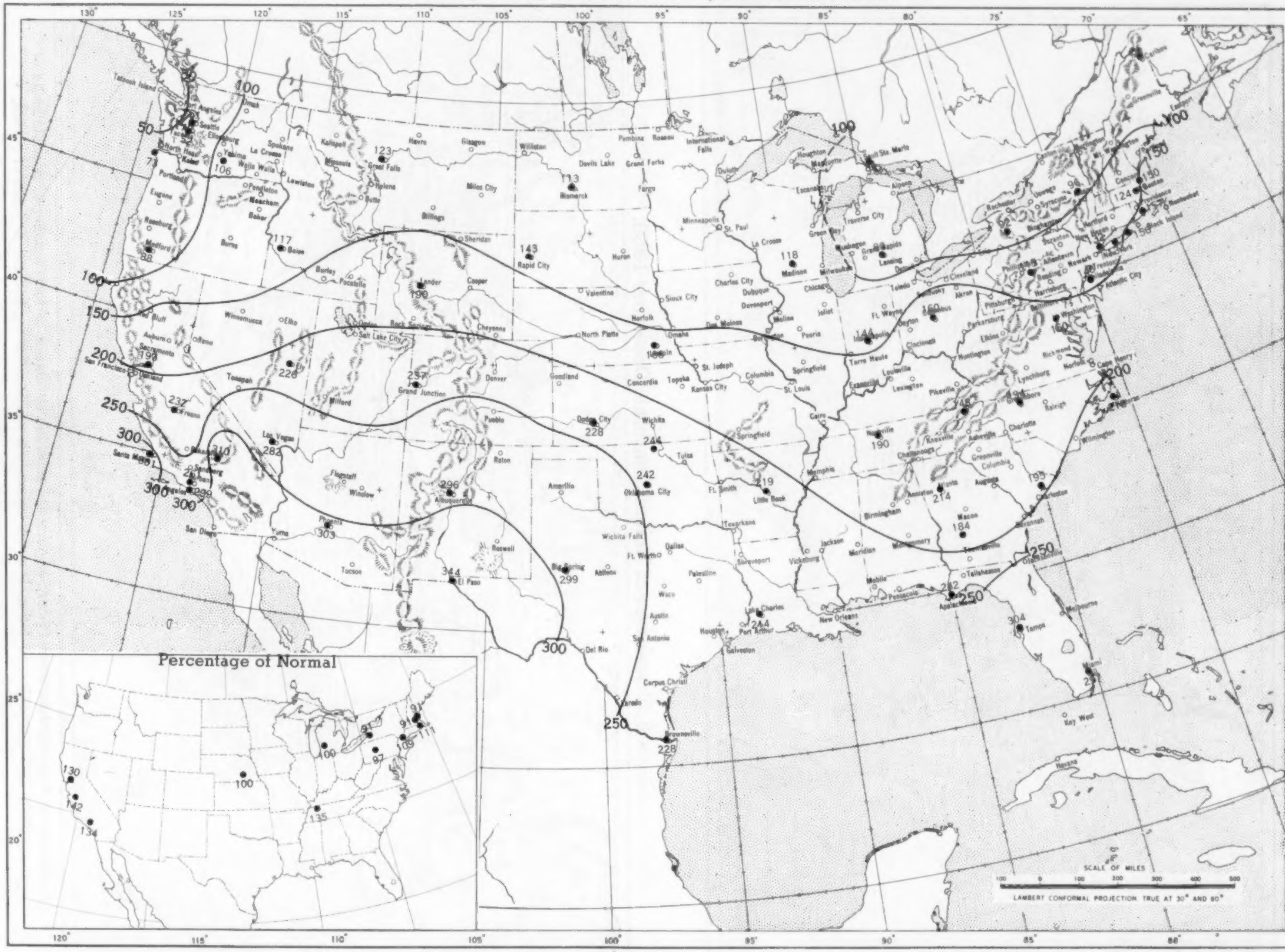
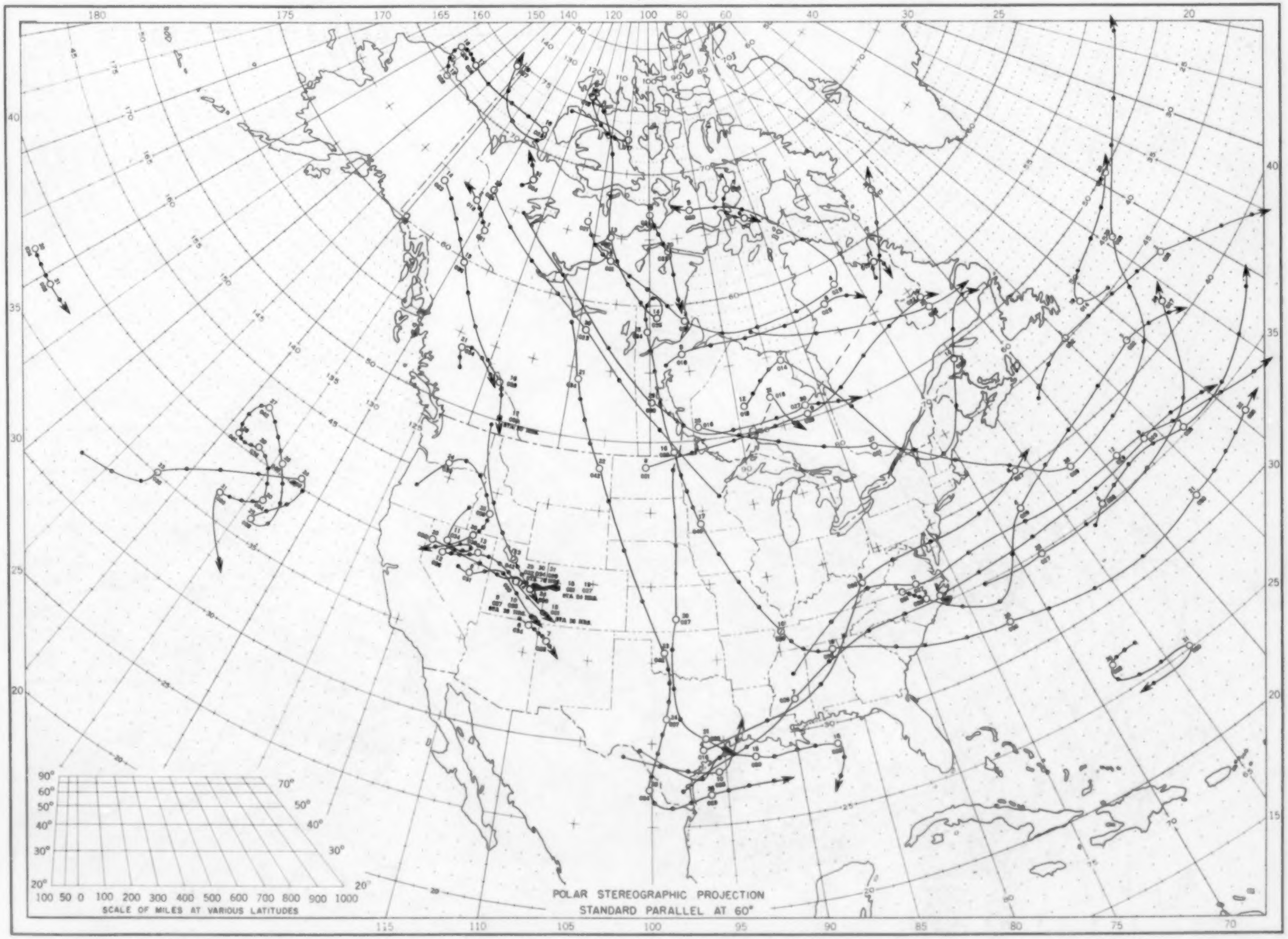


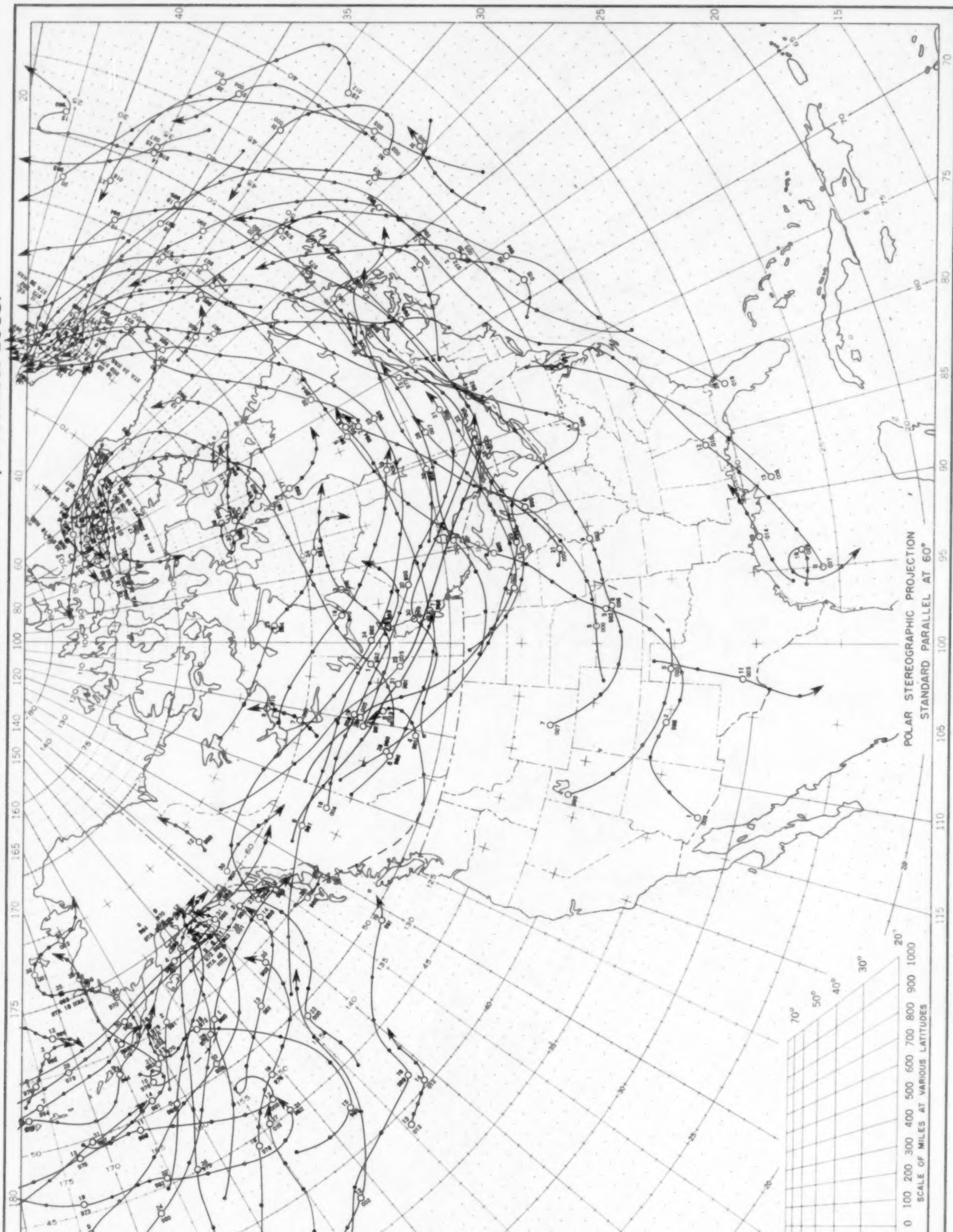
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm.$^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, December 1953.



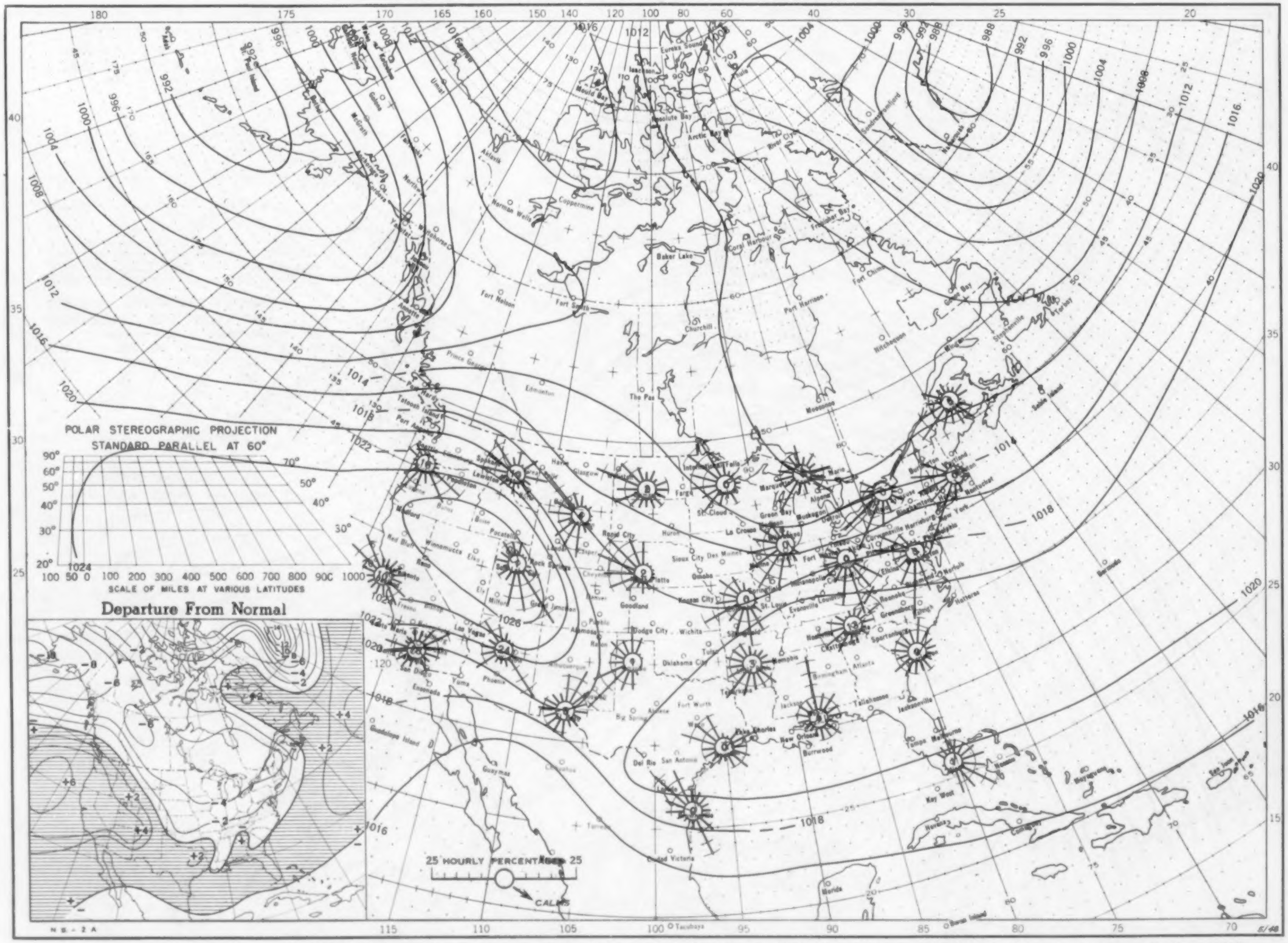
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, December 1953.



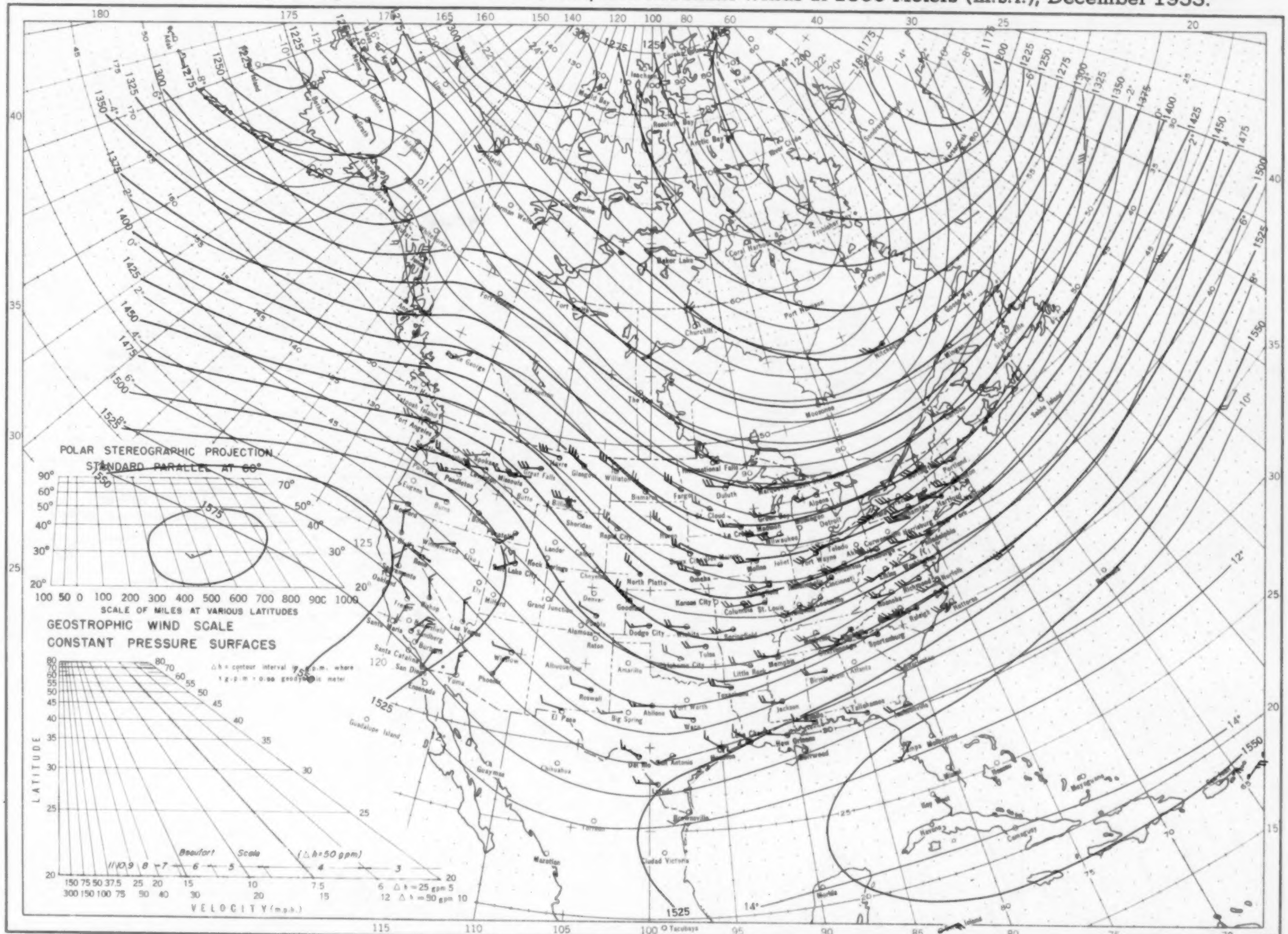
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, December 1953. Inset: Departure of Average Pressure (mb.) from Normal, December 1953.



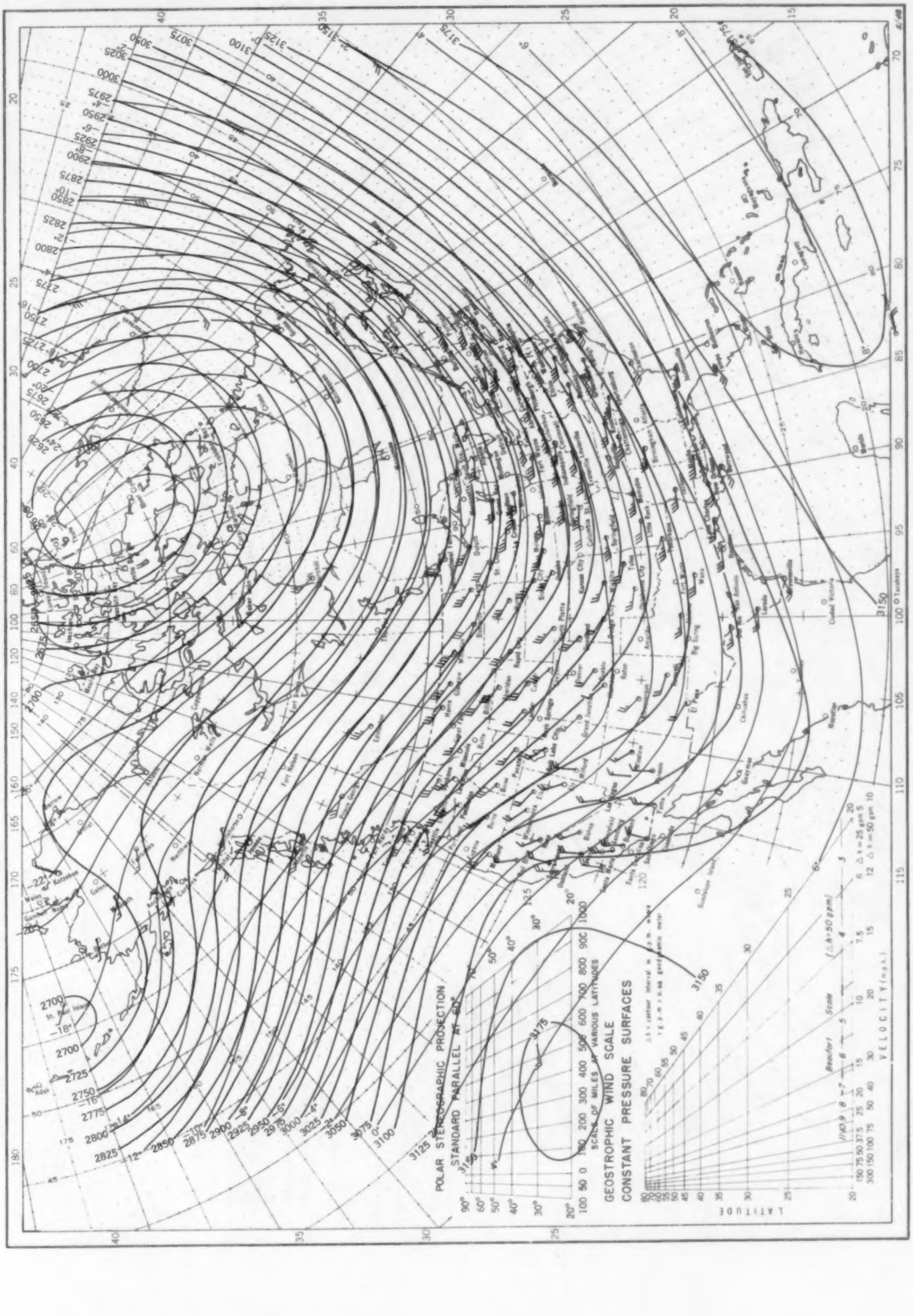
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), December 1953.



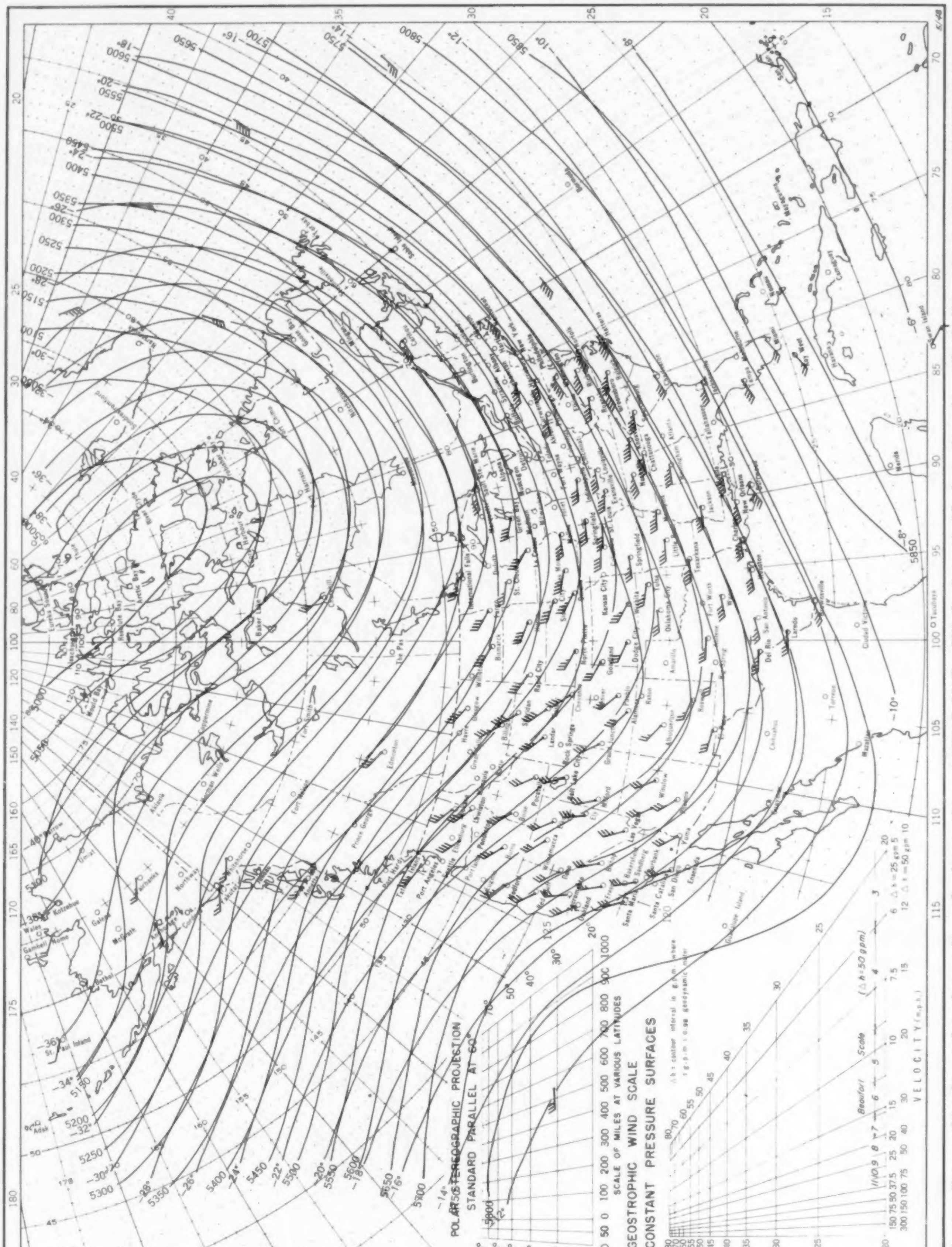
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), December 1953.



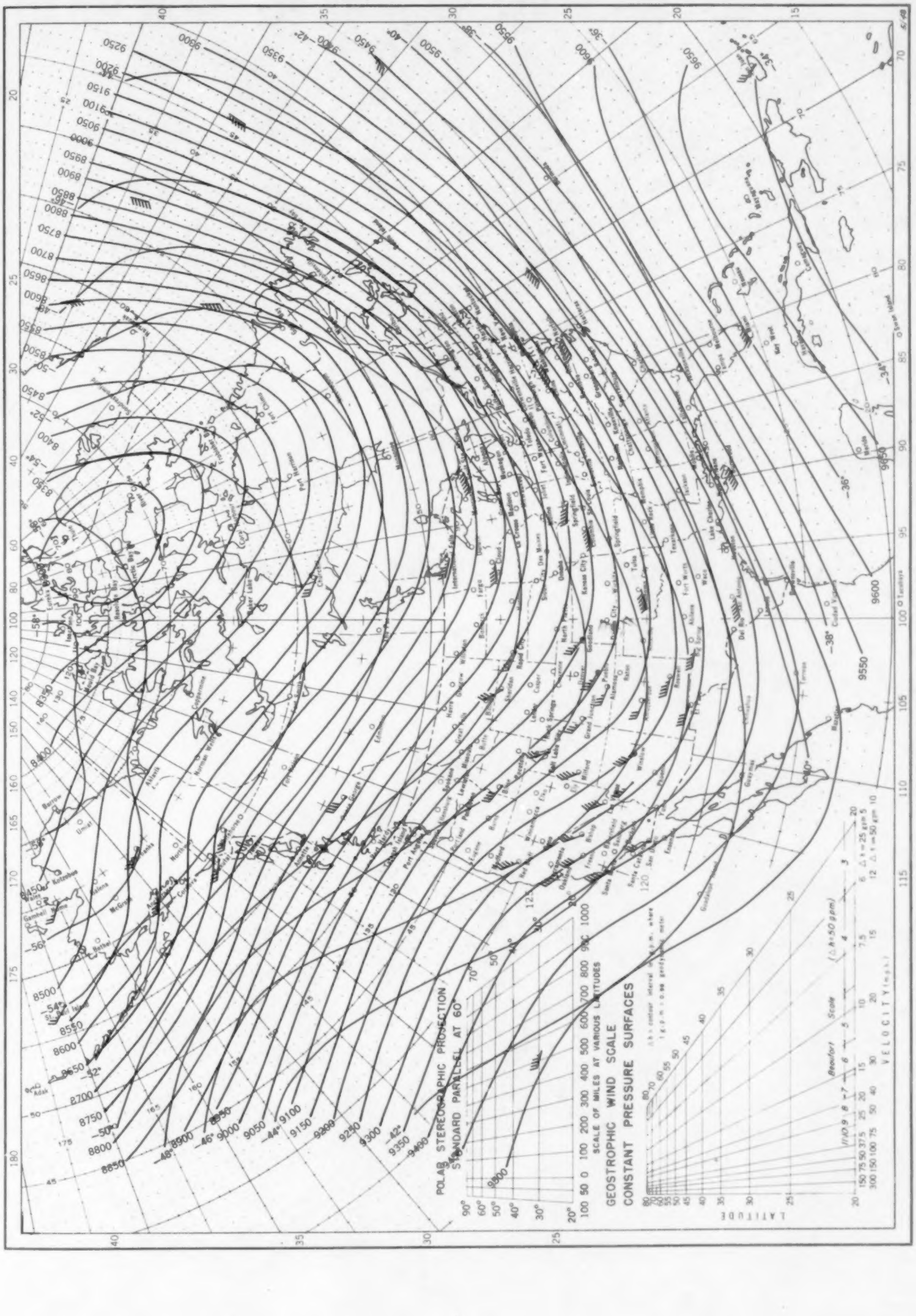
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), December 1953.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), December 1953.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

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(Continued from inside front cover)

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